Terahertz Heterodyne Receivers for Astrophysics

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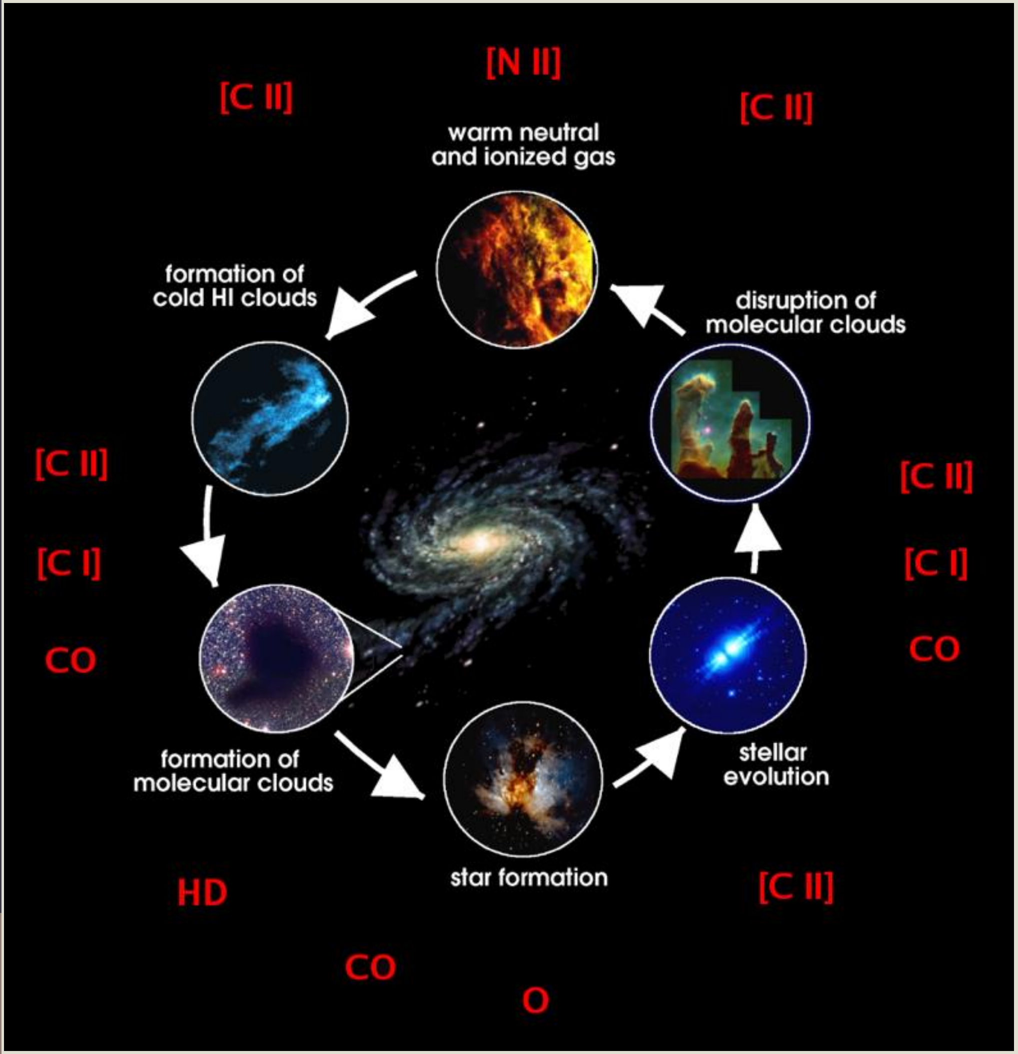
Brief Outline

- Introduction to terahertz astronomy and instrumentation
- 1.9 THz 4-pixel receiver
- 4.7 THz receiver
- Observing Platform: STO-2
- Future Directions and Conclusions

INTRODUCTION TO TERAHERTZ ASTRONOMY AND INSTRUMENTATION

Key Science Questions



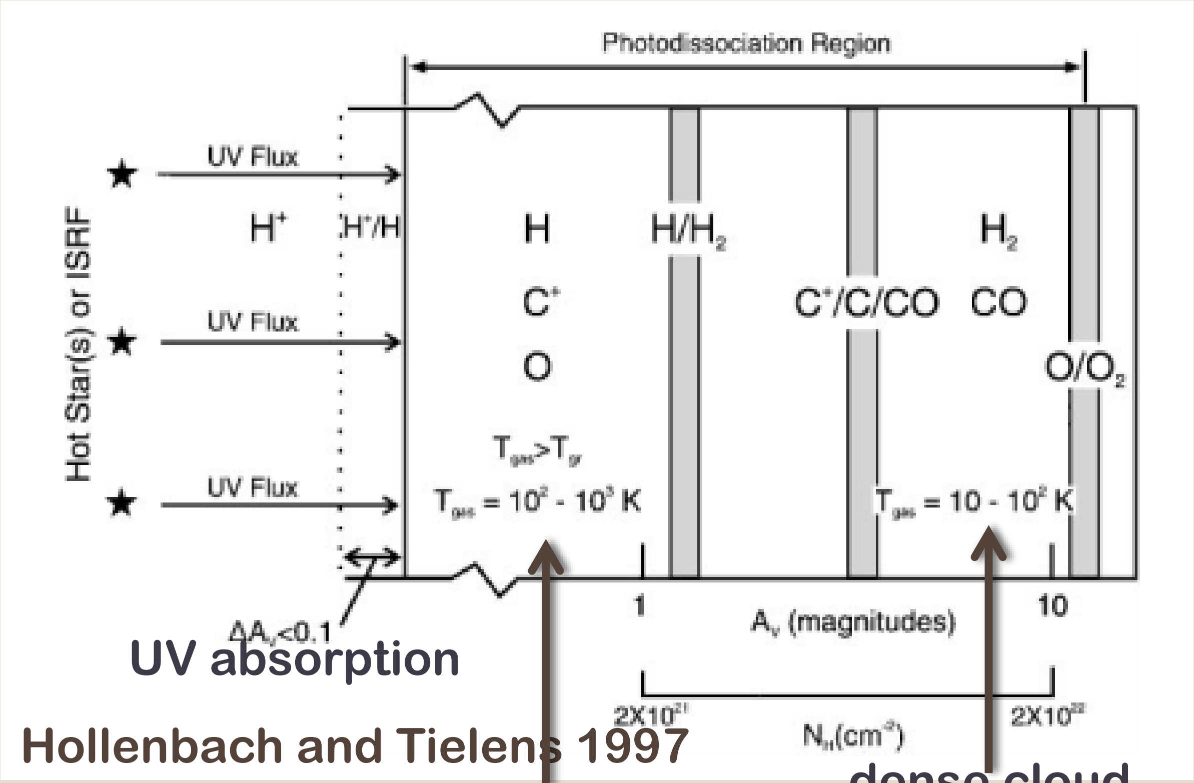
The lifecycle of the Interstellar Medium (ISM); Image Credit: C. Kulesa

- How and where are interstellar clouds made, and how long do they live?
- Under what conditions and at what rate do clouds form stars?
- How do stars return enriched material back to the Galaxy?
- How do these processes sculpt the evolution of galaxies?

Photodissociation Regions (PDRs)

- PDRs are the boundary regions between the ionizing UV photons and cooler, denser, neutral regions in the galaxy

- Example: giant molecular clouds (GMCs)



UV absorption

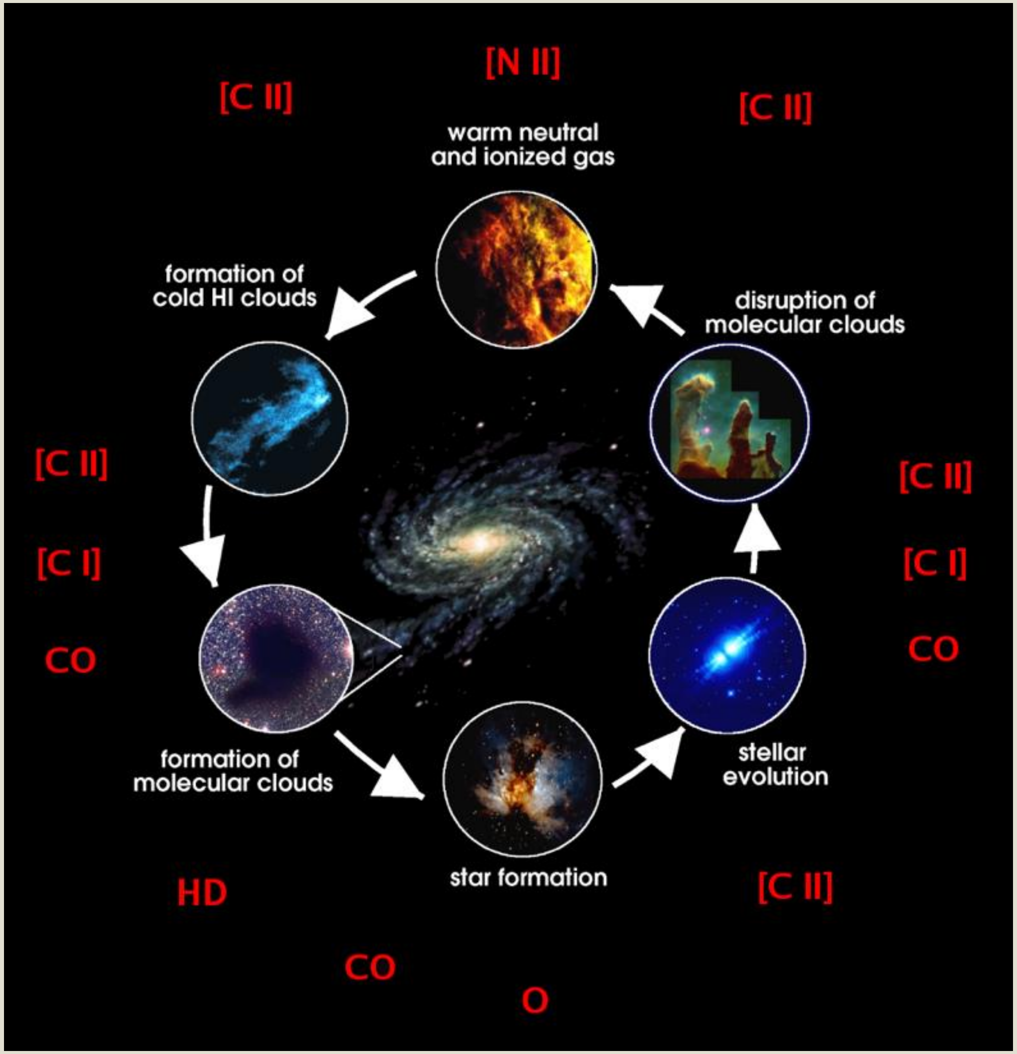
Hollenbach and Tielens 1997

diffuse cloud properties

dense cloud properties

- A better understanding of PDRs will provide insight into how GMCs are formed in the ISM and the shielding they provide for stellar nurseries

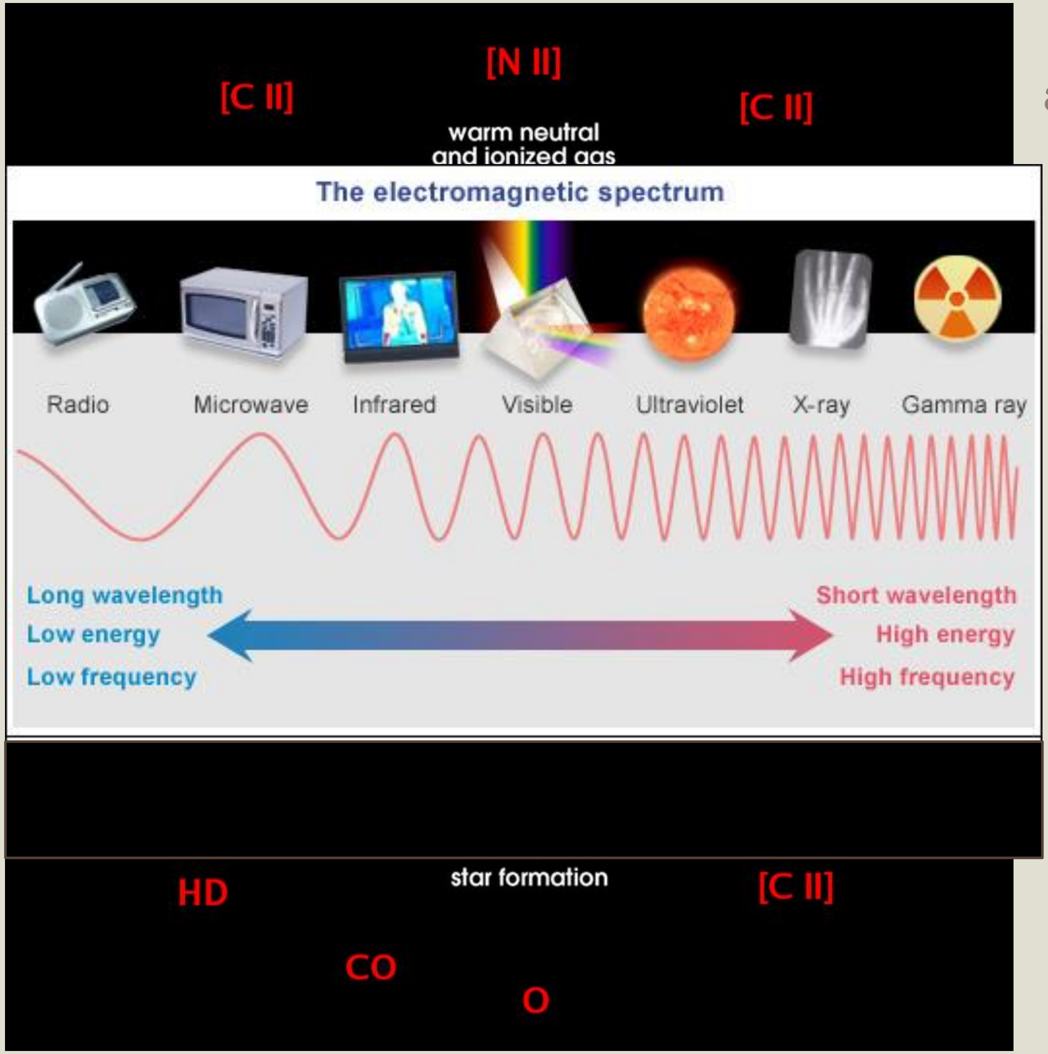
Life Cycle of Interstellar Medium (ISM)



What do all of these atomic and molecular tracers have in common?

Image Credit: Kulesa and Walker

Life Cycle of Interstellar Medium (ISM)

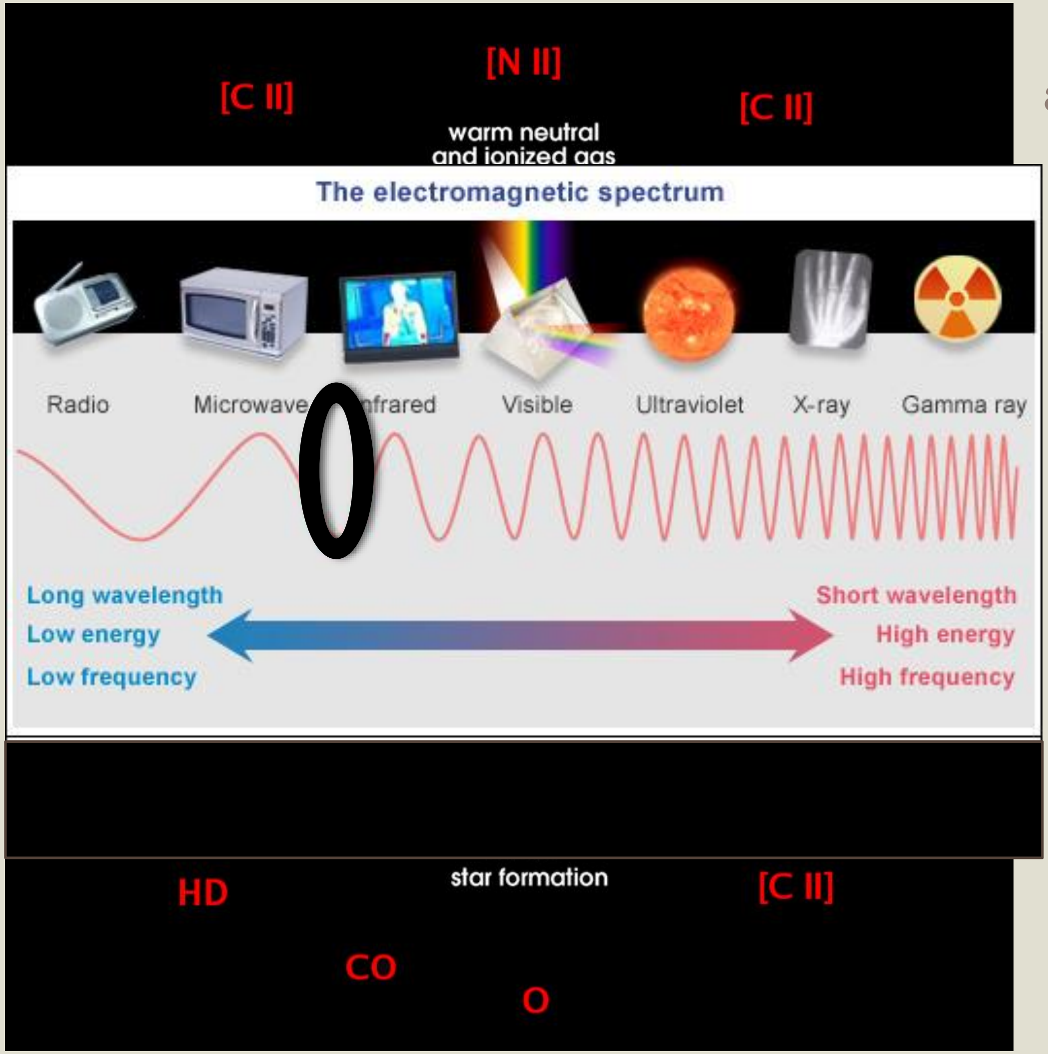


What do all of these atomic and molecular tracers have in common?

Transitions in the THz/Sub-millimeter (300 GHz – 3 THZ)!

Image Credit: Kulesa and Walker

Life Cycle of Interstellar Medium (ISM)



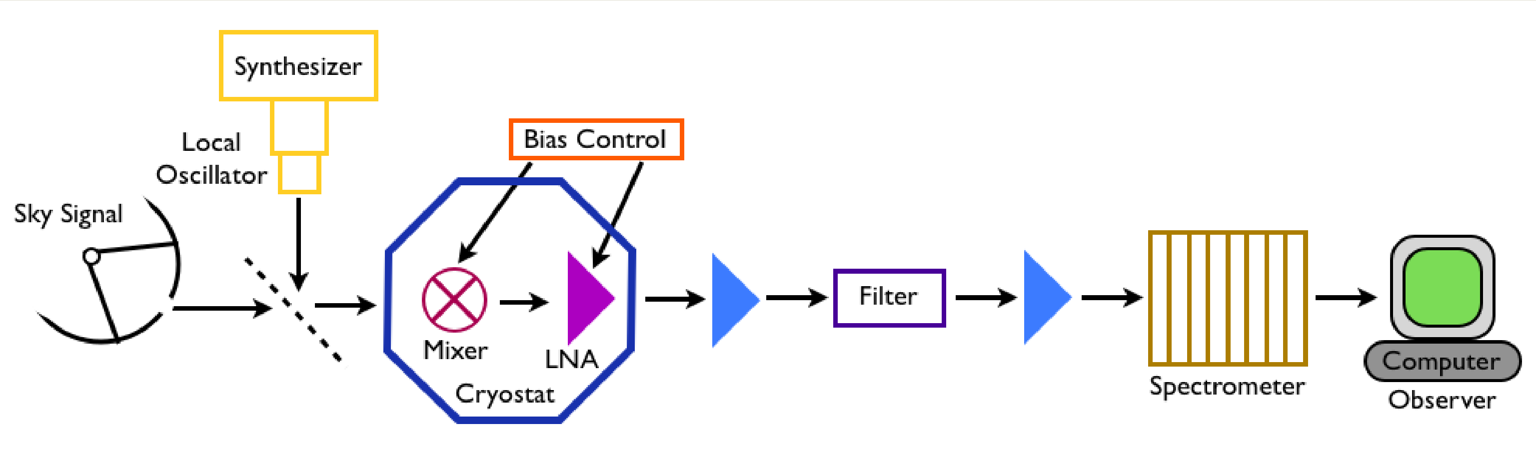
What do all of these atomic and molecular tracers have in common?

Transitions in the THz/Sub-millimeter (300 GHz – 3 THZ)!

Large scale THz spectroscopic surveys are needed to study the kinematics of large gas clouds in the Milky Way => heterodyne arrays needed!

Image Credit: Kulesa and Walker

Superconducting THz Heterodyne Receiver



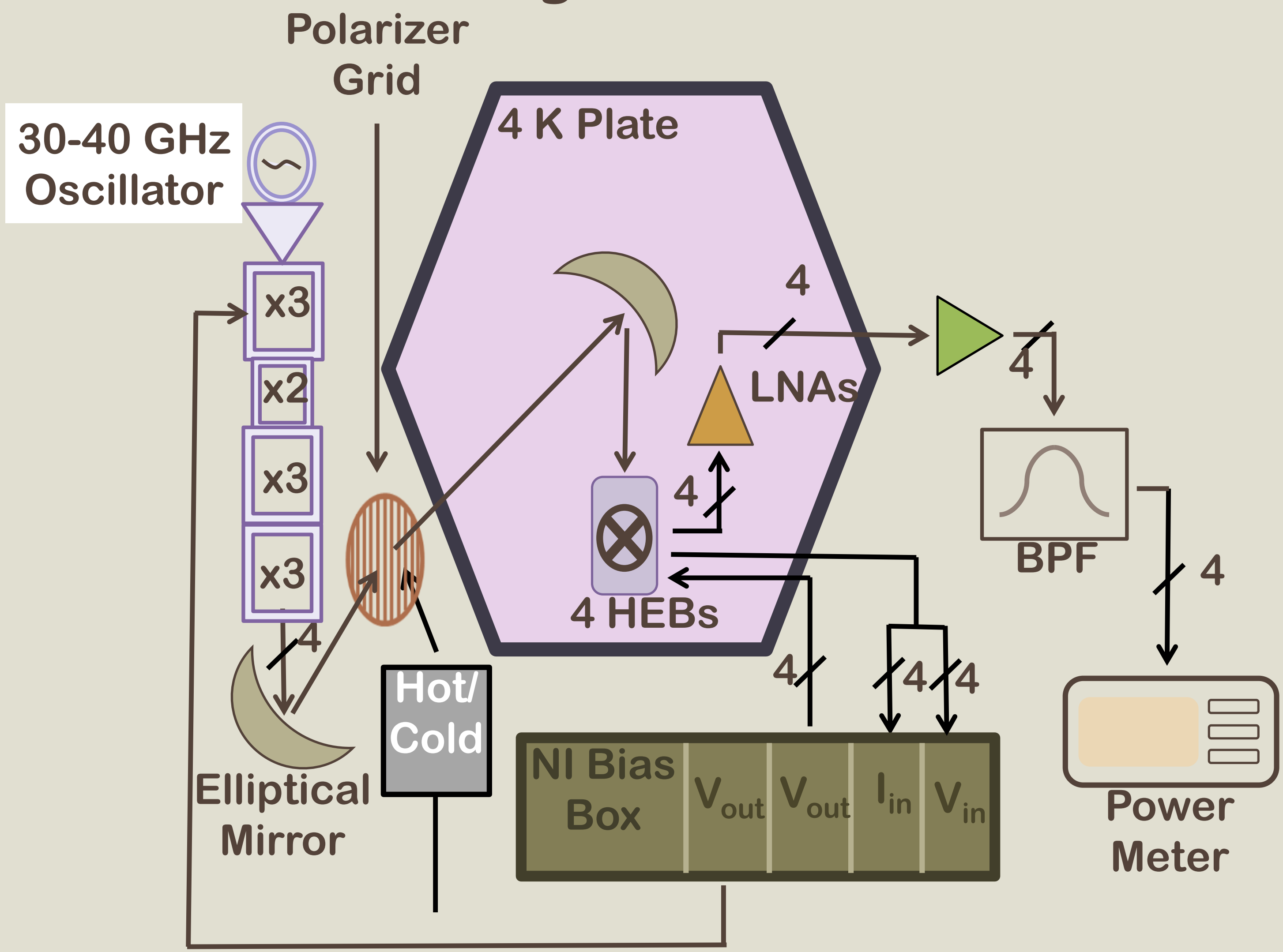
Kloosterman 2014

- Coherent detection
- High spectral resolution ($R=10^7$)
- Sensitivity
- SIS or HEB Mixers

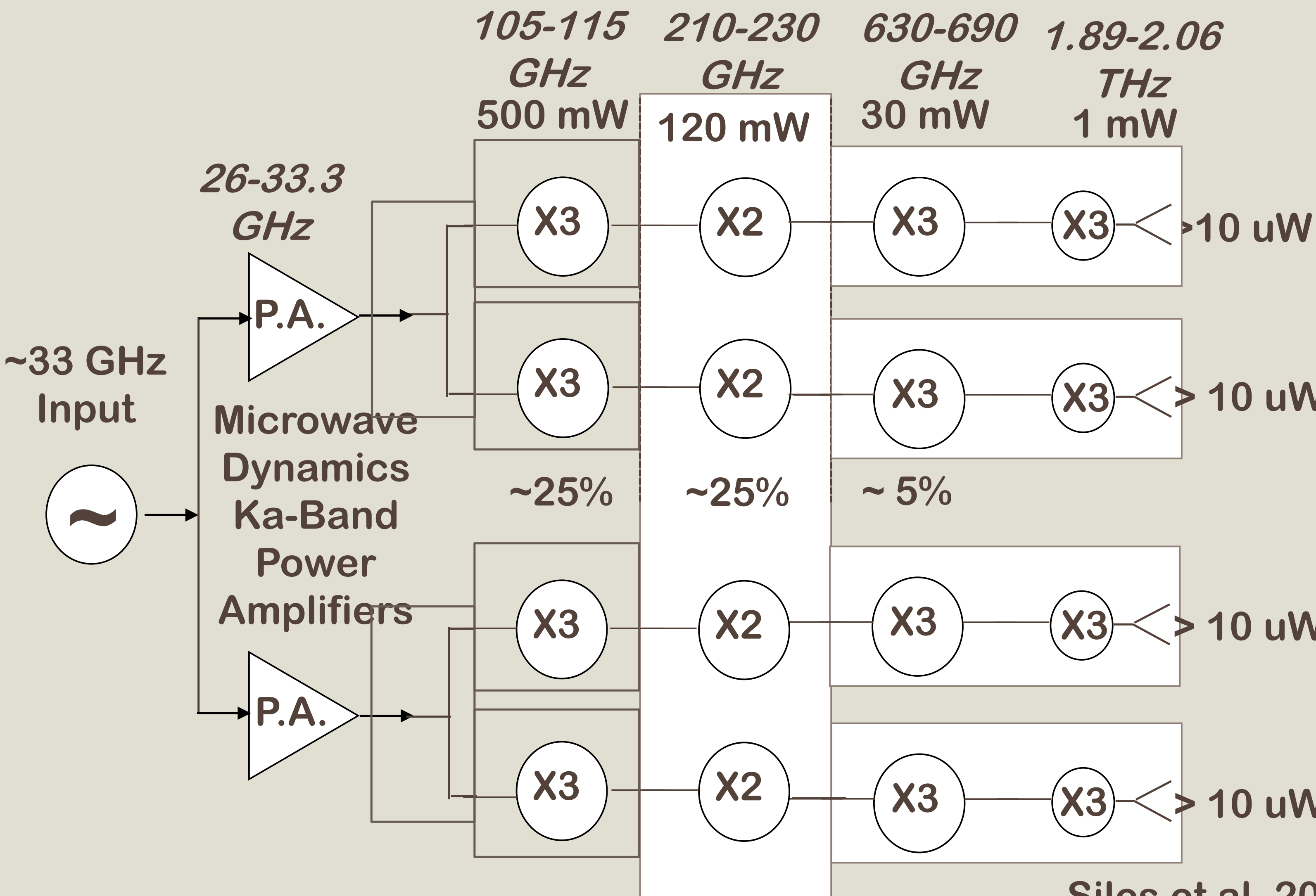
1.9 THZ 4-PIXEL RECEIVER

For the 158 μm fine structure line in ionized carbon.

Lab Setup for Prototype Array at 1.9 THz

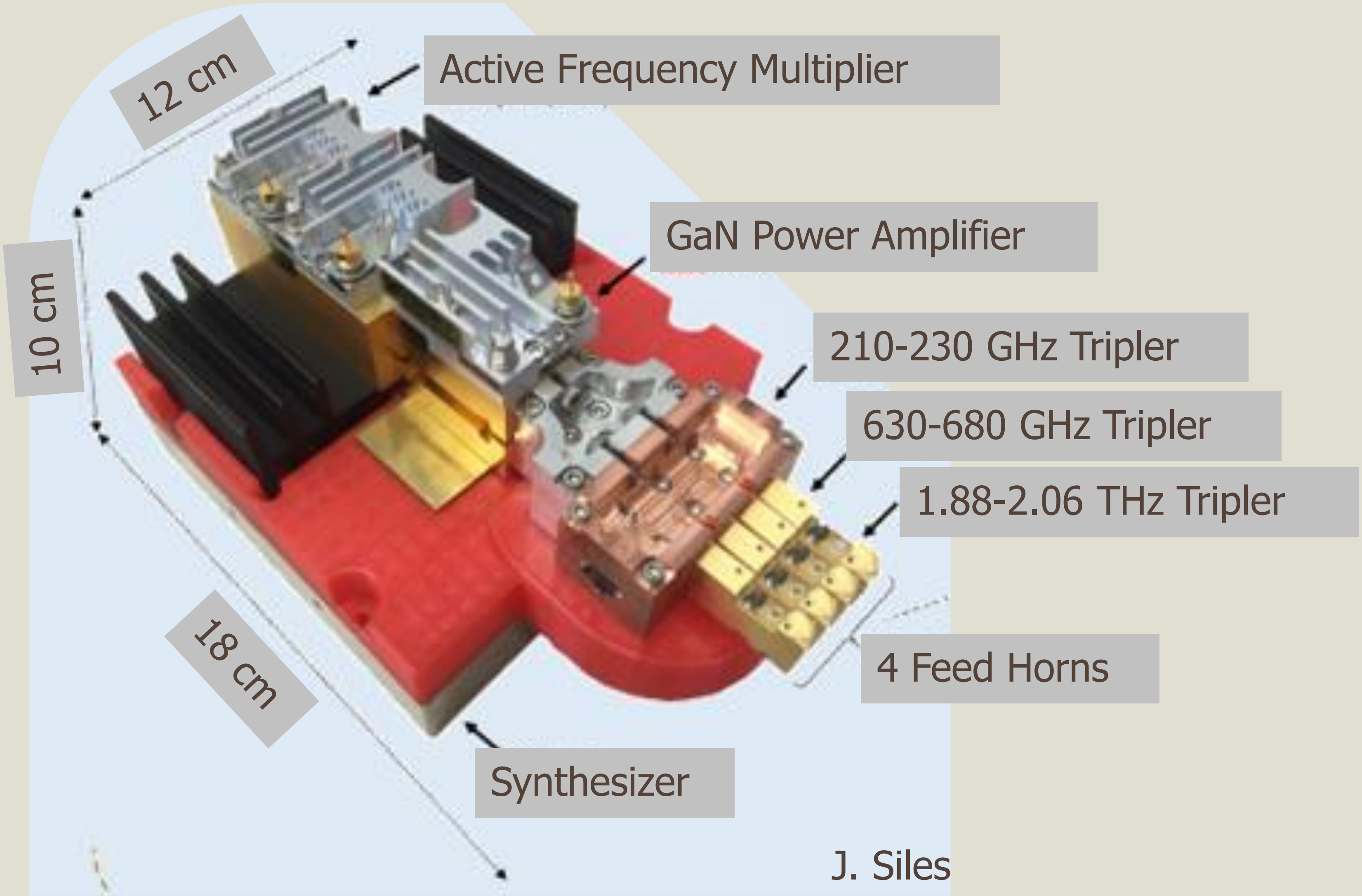


1.9 THz Local Oscillator

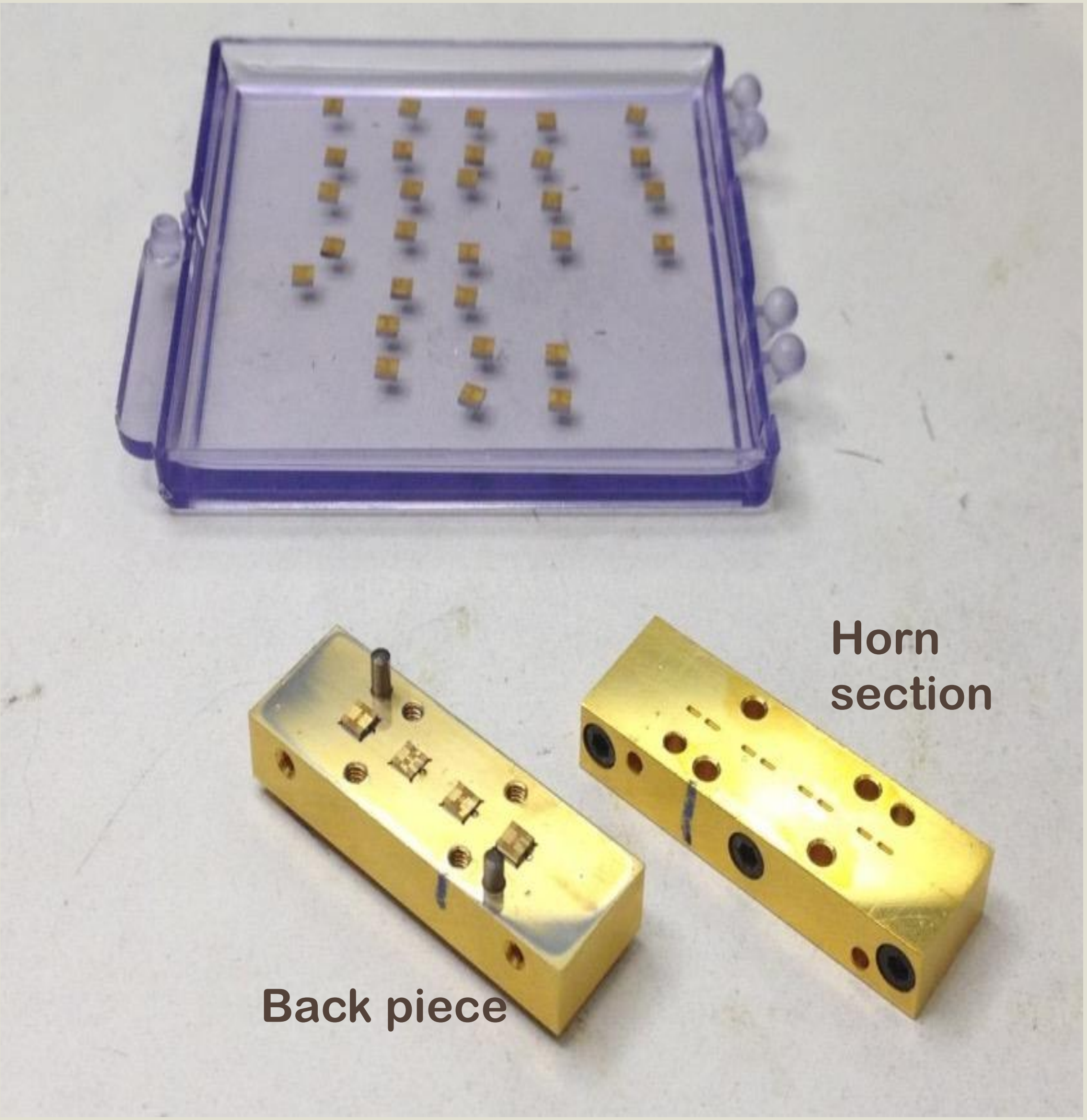


Siles et al. 2014

Local Oscillator: 4-Pixel Multiplier Chain

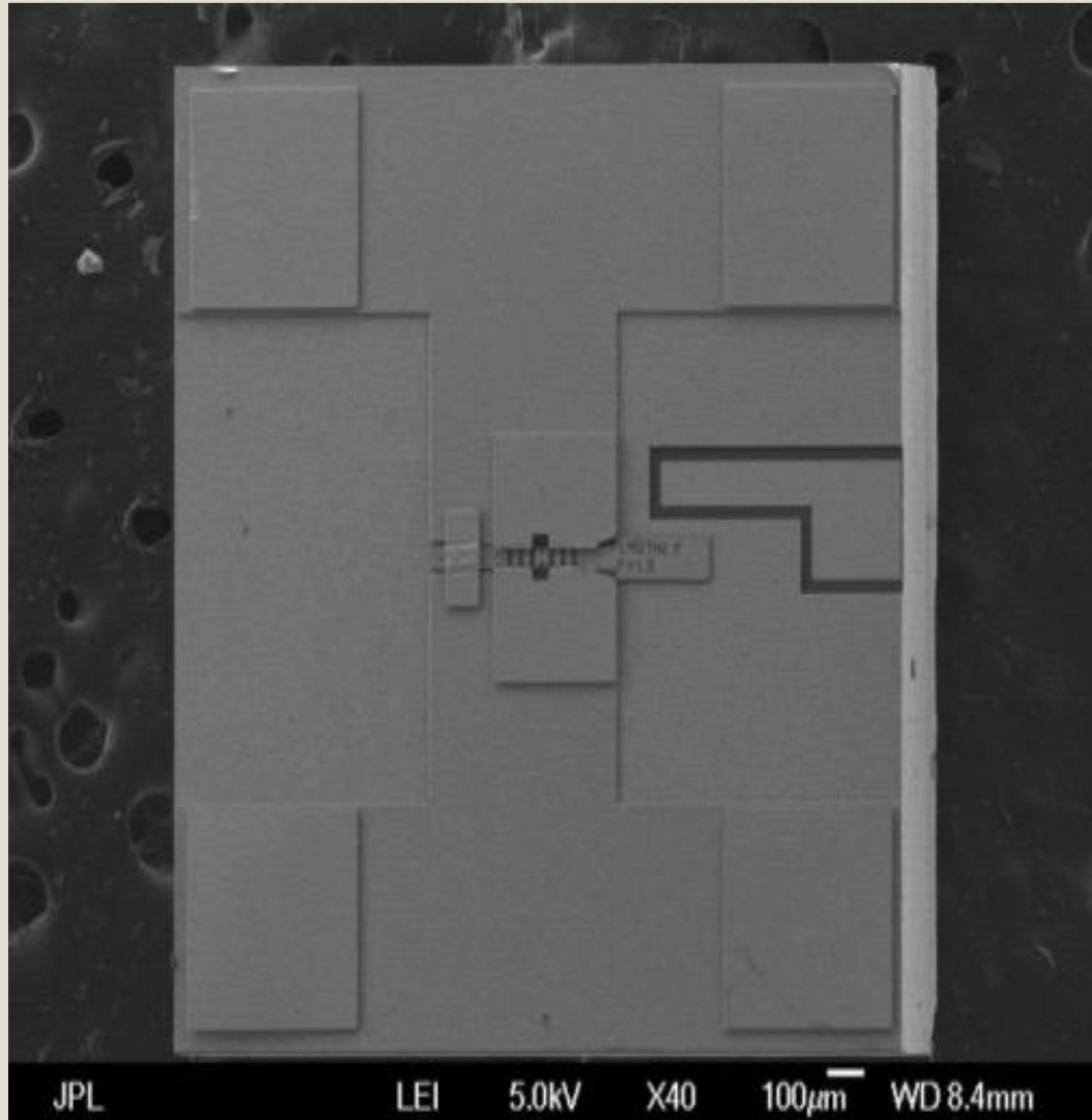


Mixers



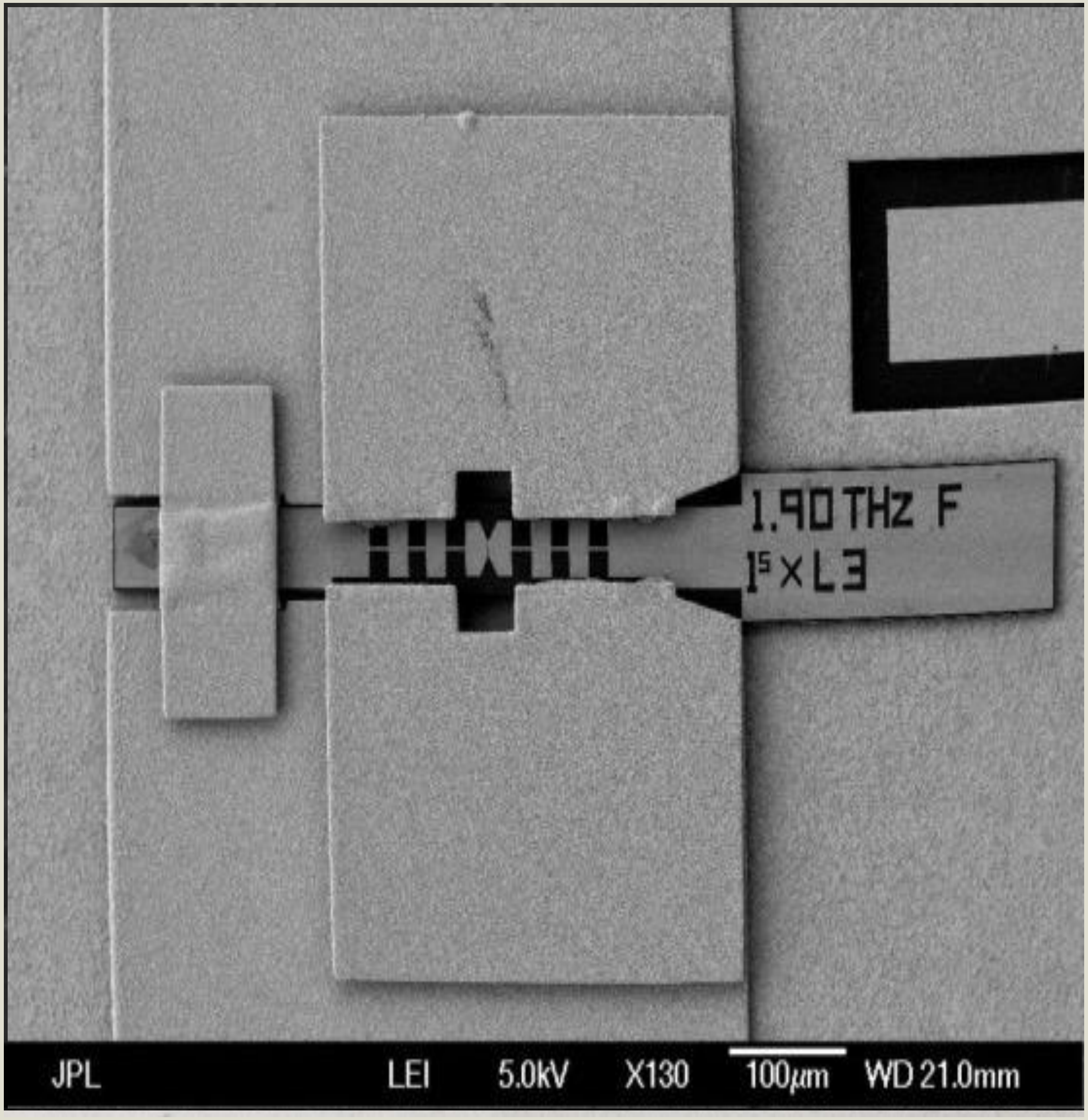
SOI Chip-HEB Technology

Mixers



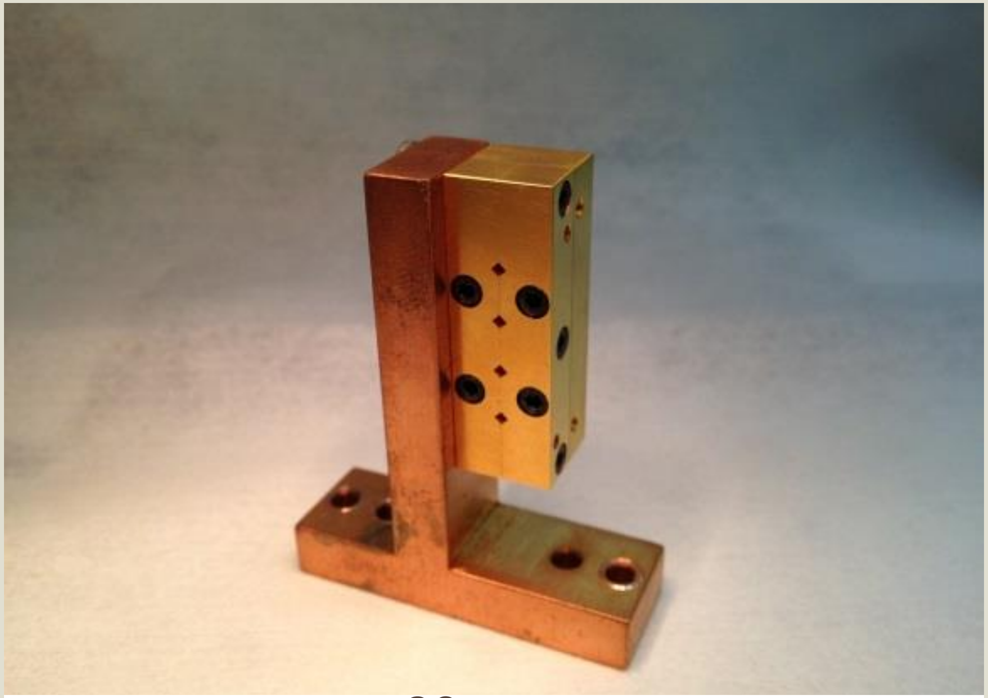
SOI Chip-HEB Technology

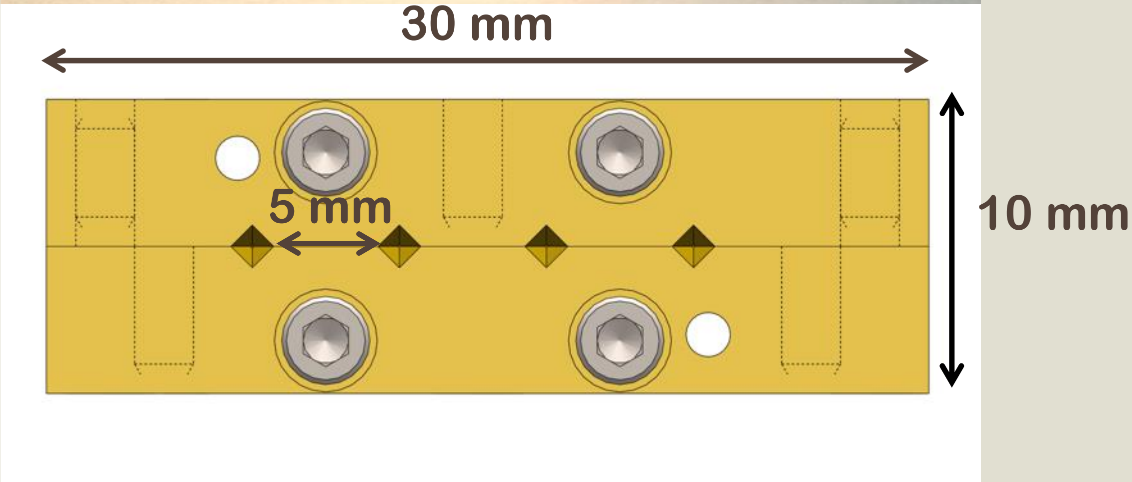
Mixers

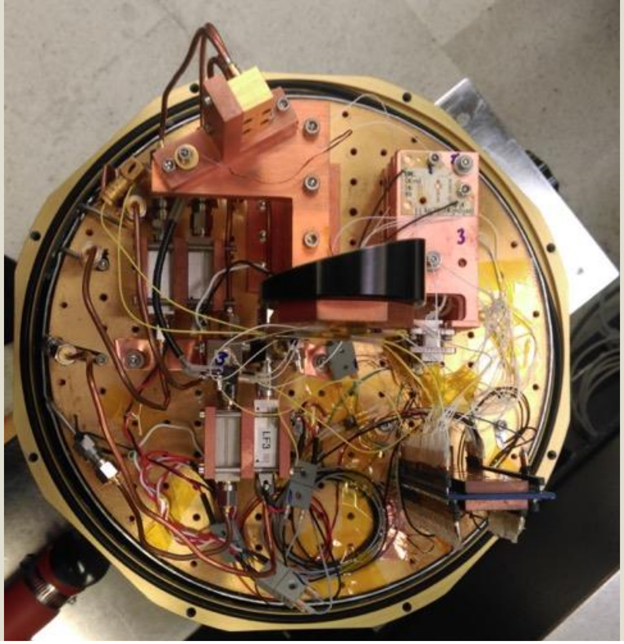


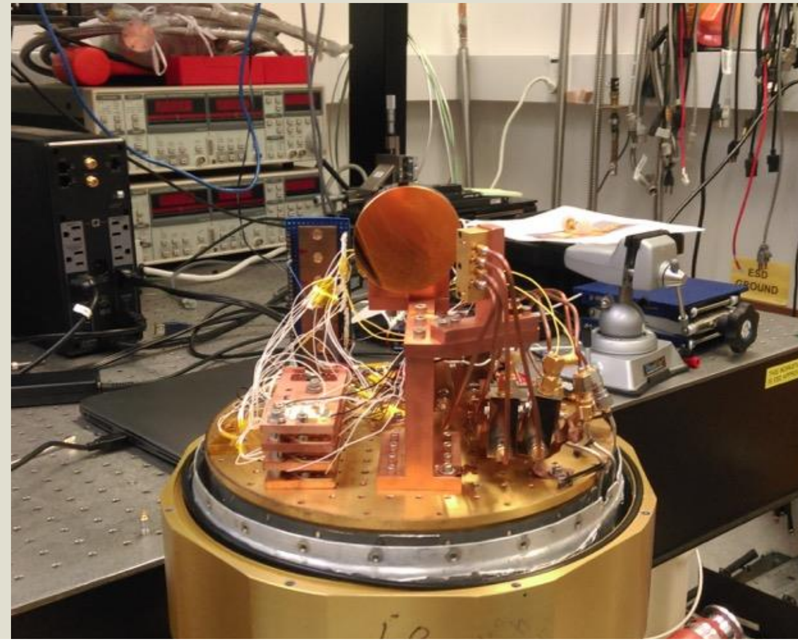
SOI Chip-HEB Technology

4-Pixel Mixer Block

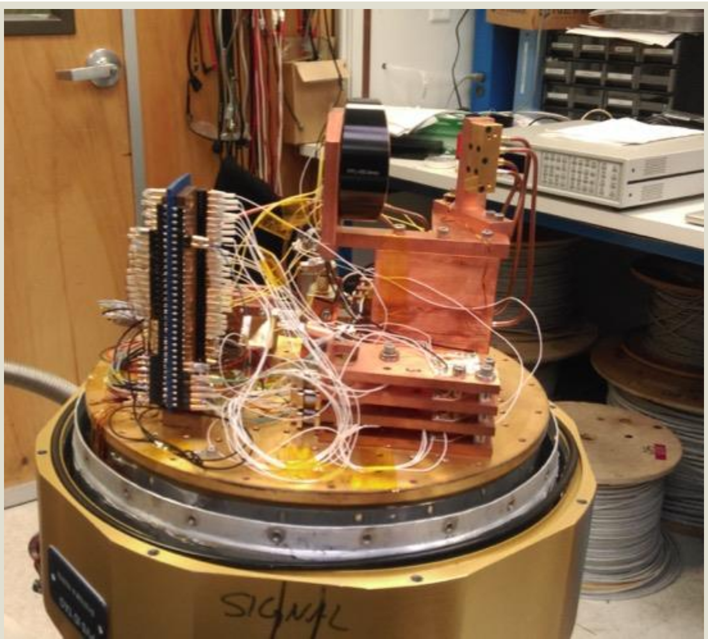


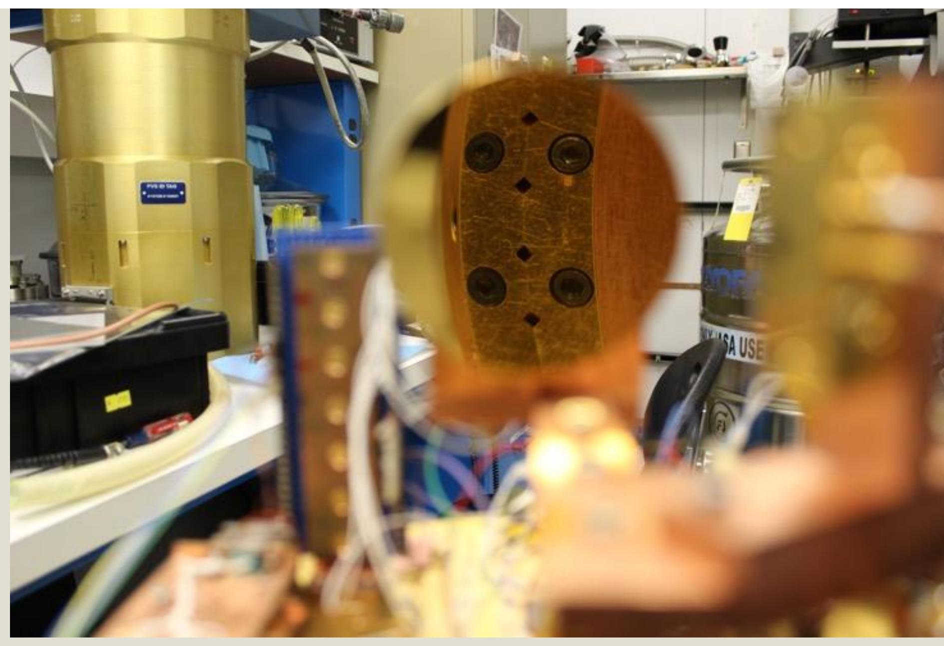




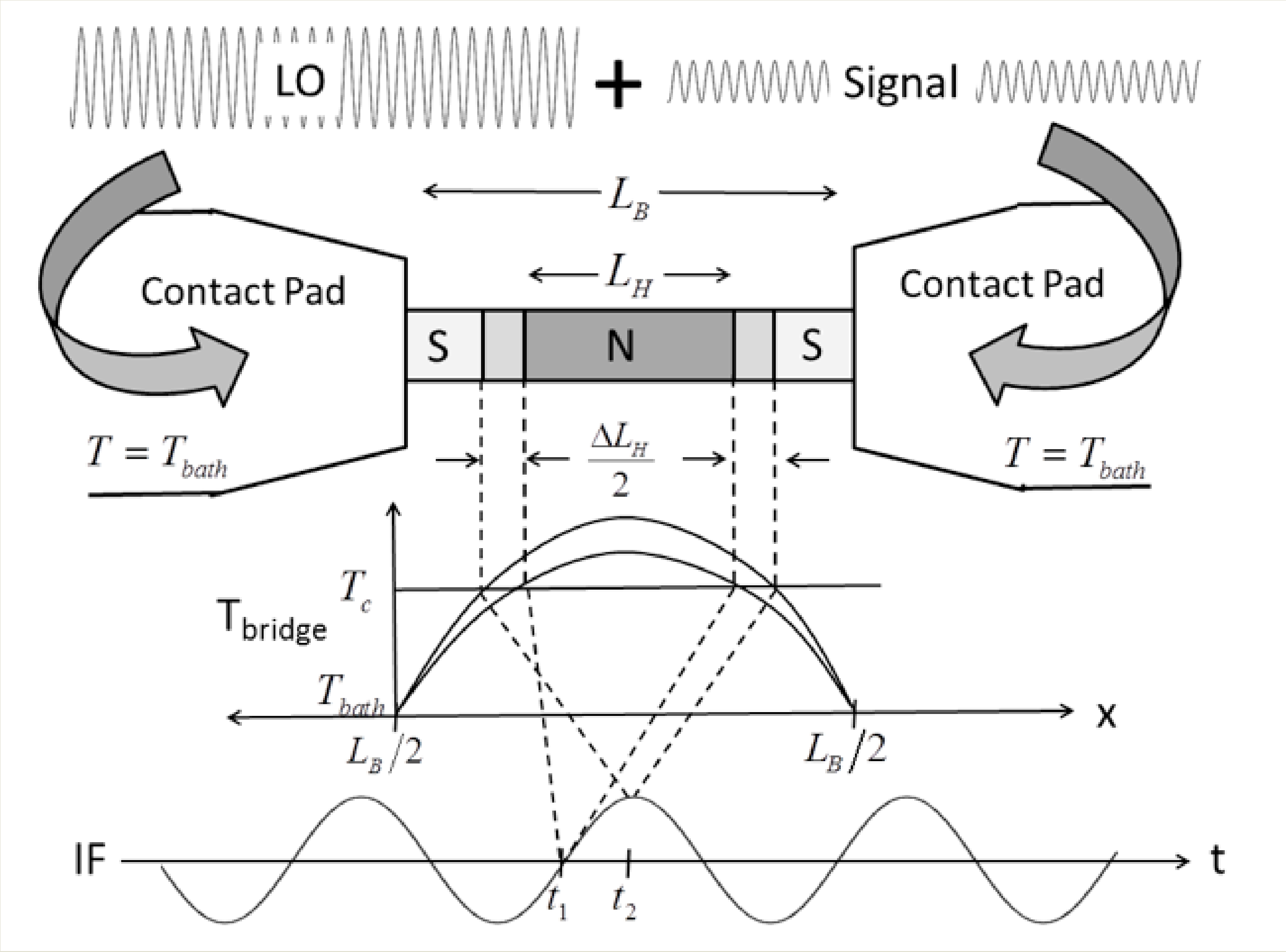


4 Pixel Array Inside the Cryostat



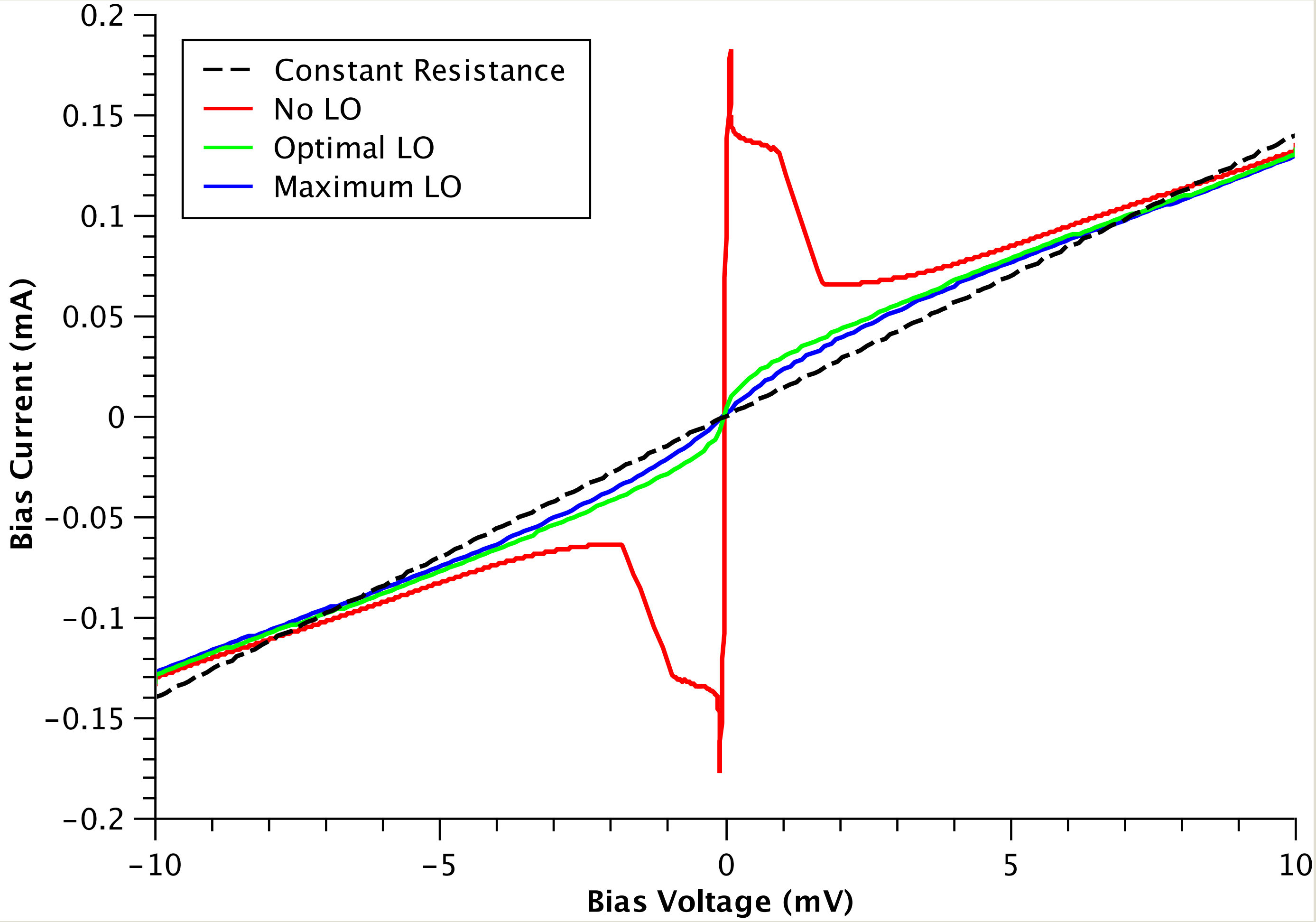


Hot Spot Mixing Model



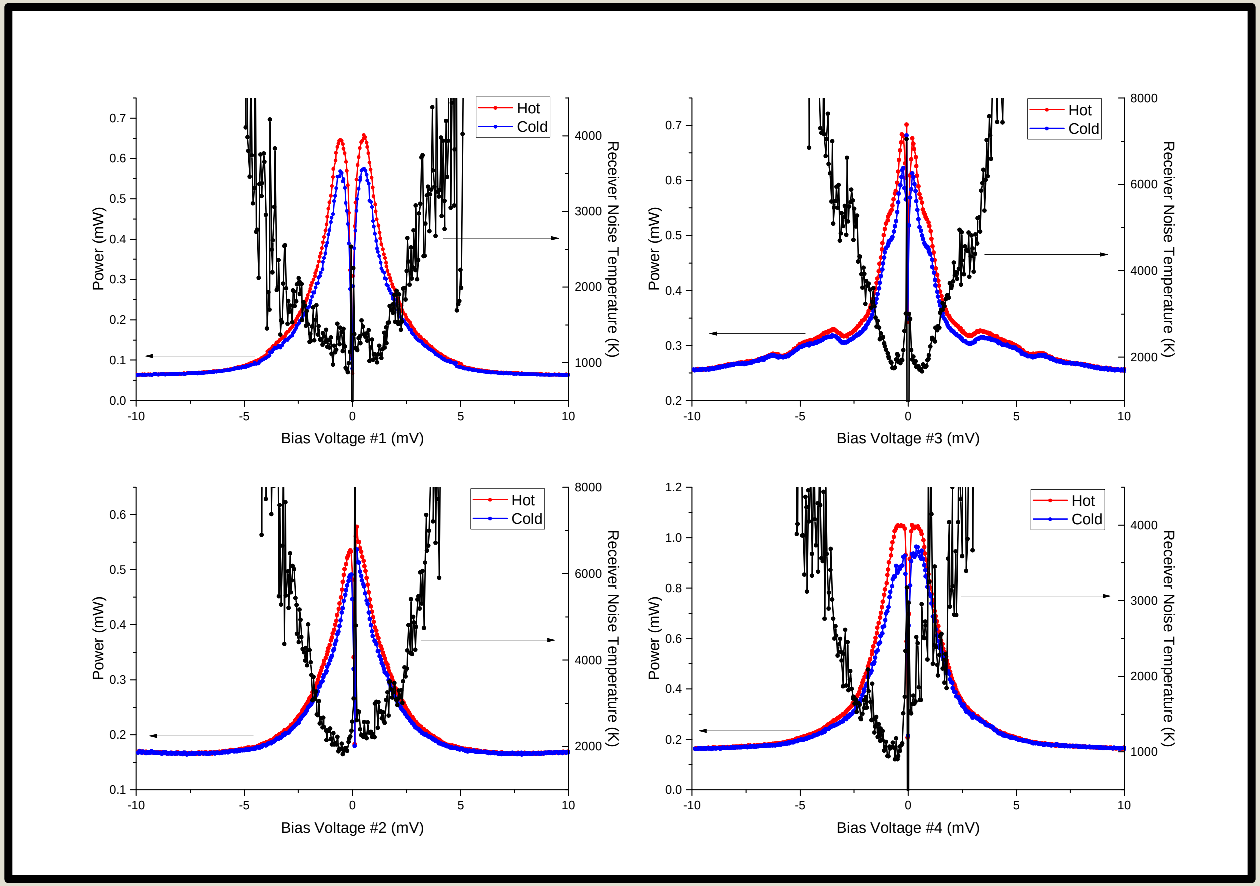
Walker 2015

HEB IV Curve



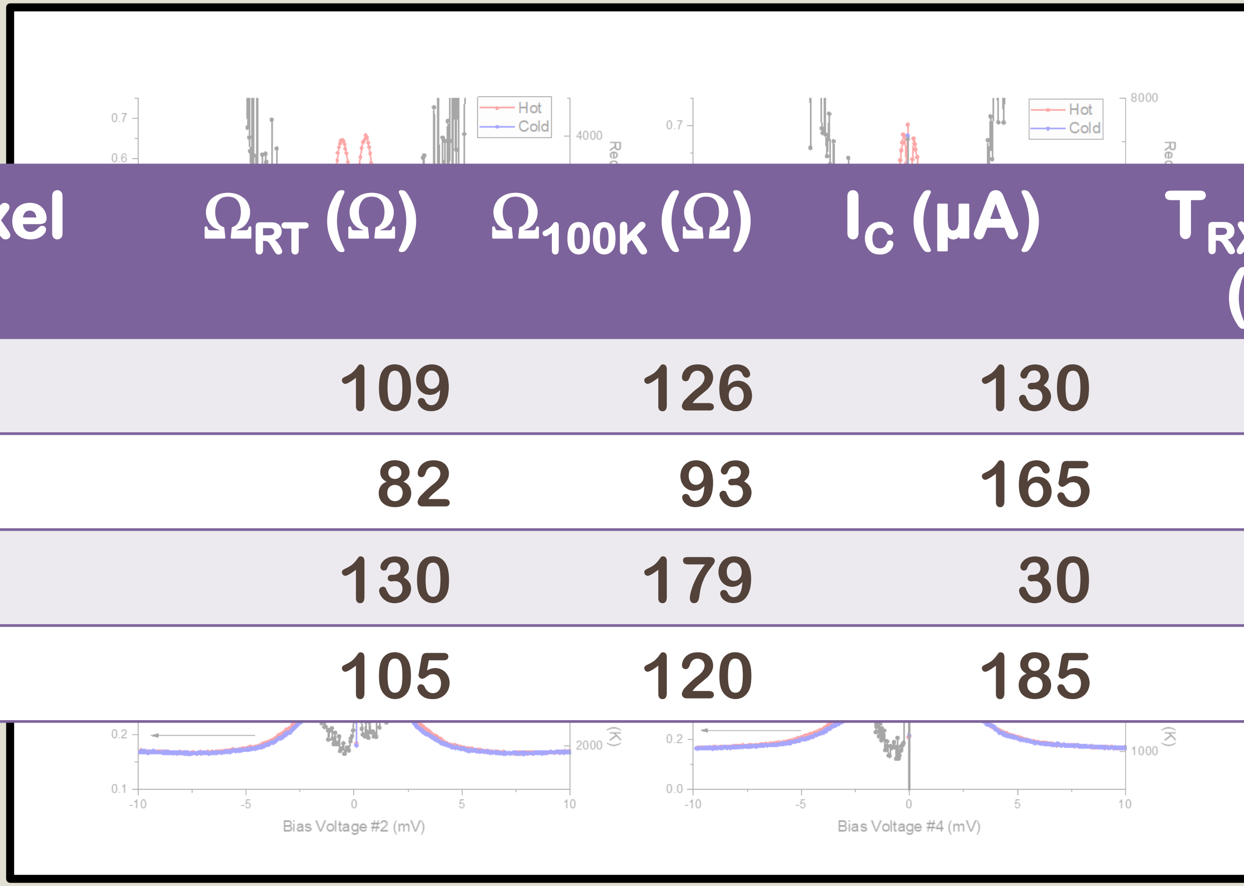
Constant Resistance
No LO
Optimal LO
Maximum LO
Bias Current (mA)
Bias Voltage (mV)
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
−10
−5
0
5
10

Lab Results



Y-factors, the ratio of a room temperature blackbody to a 77 K blackbody, are measured to determine receiver sensitivity.

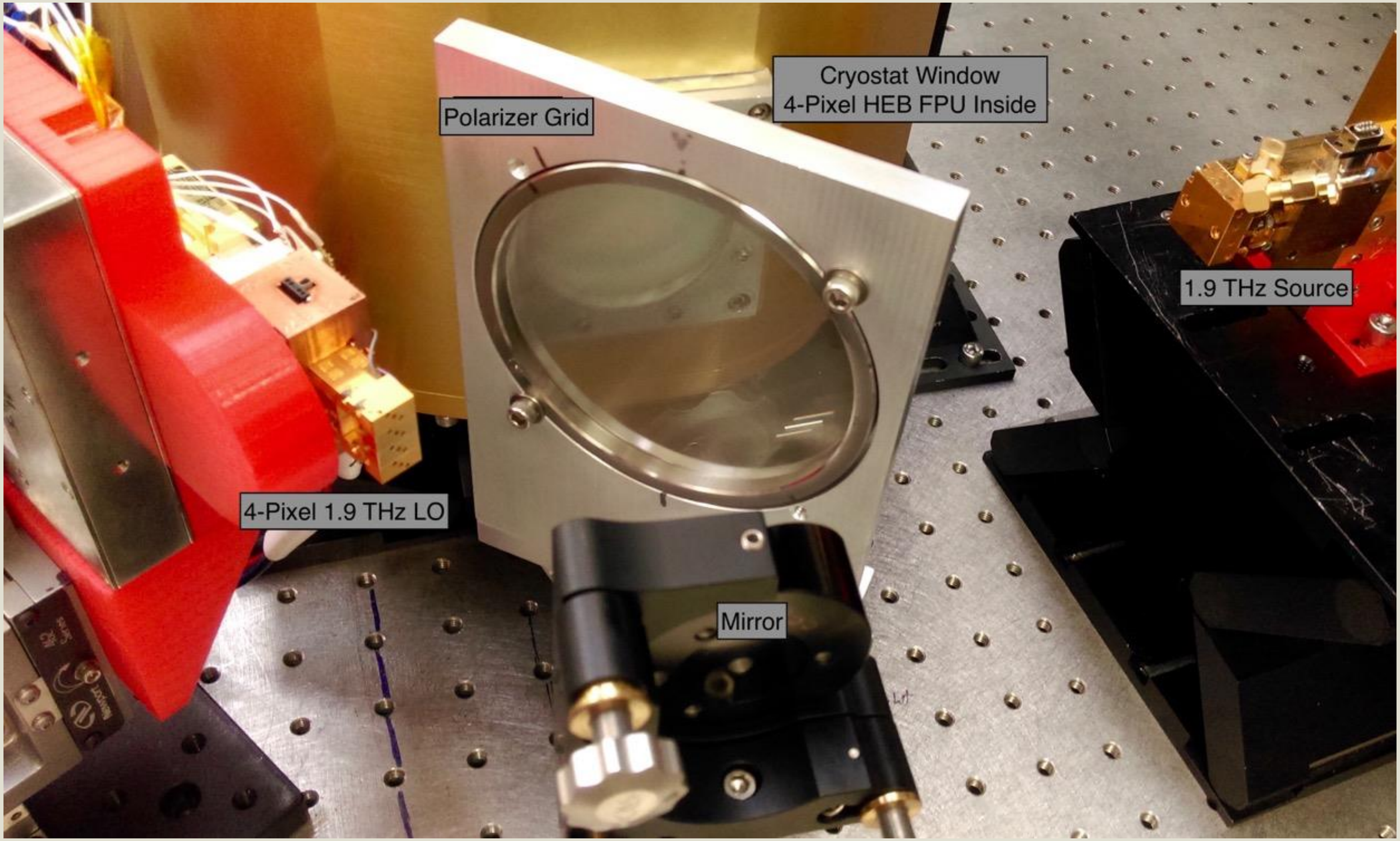
Lab Results



Pixel	Ω_{RT} (Ω)	Ω_{100K} (Ω)	I_C (μA)	$T_{RX, DSB}$ (K)
1	109	126	130	900
2	82	93	165	1800
3	130	179	30	1700
4	105	120	185	900

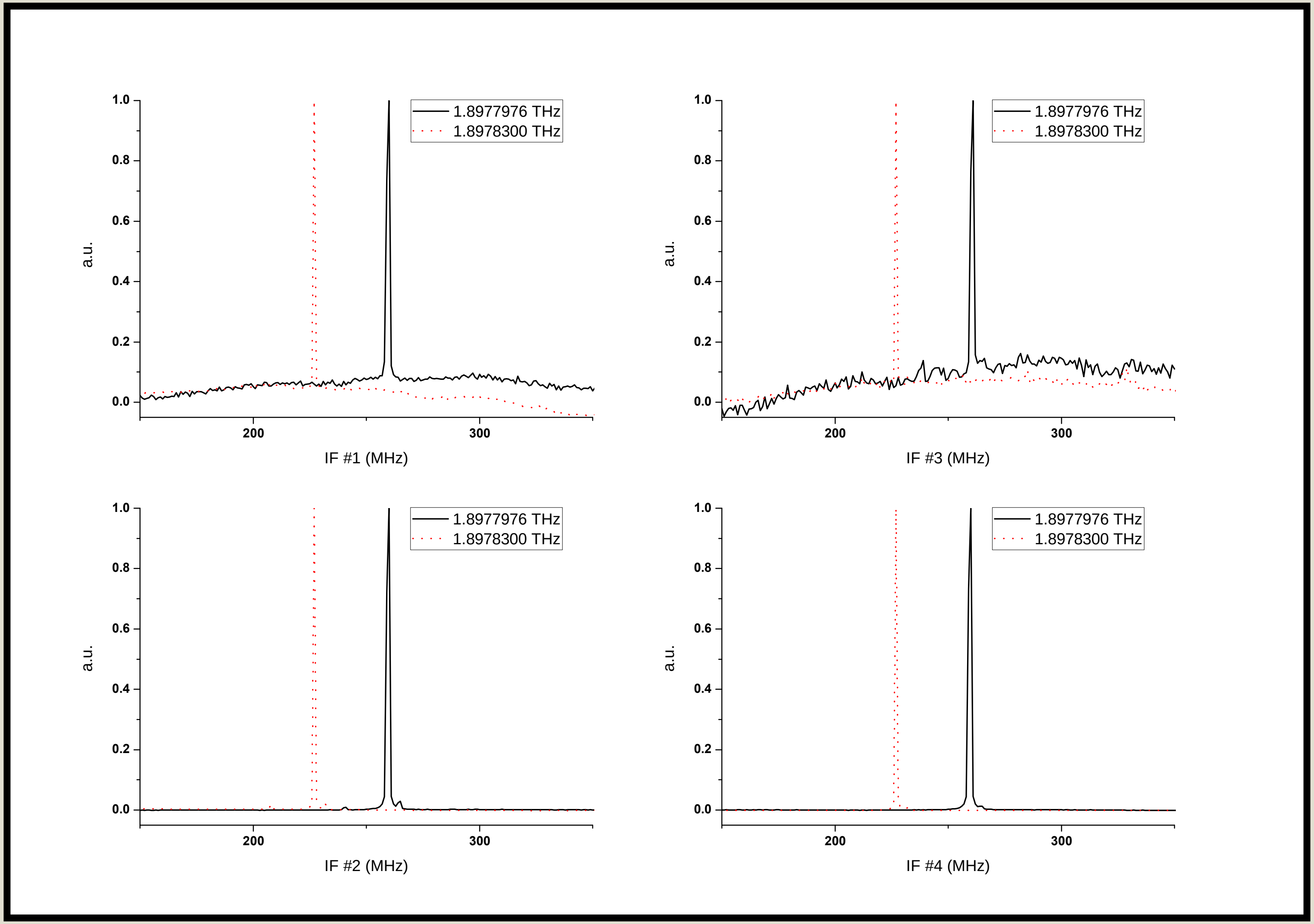
Y-factors, the ratio of a room temperature blackbody to a 77 K blackbody, are measured to determine receiver sensitivity.

Lab Setup for 1.9 THz Spectra



Measurement setup for 4-pixel heterodyne array receiver verification at 1.9 THz.

Lab Results

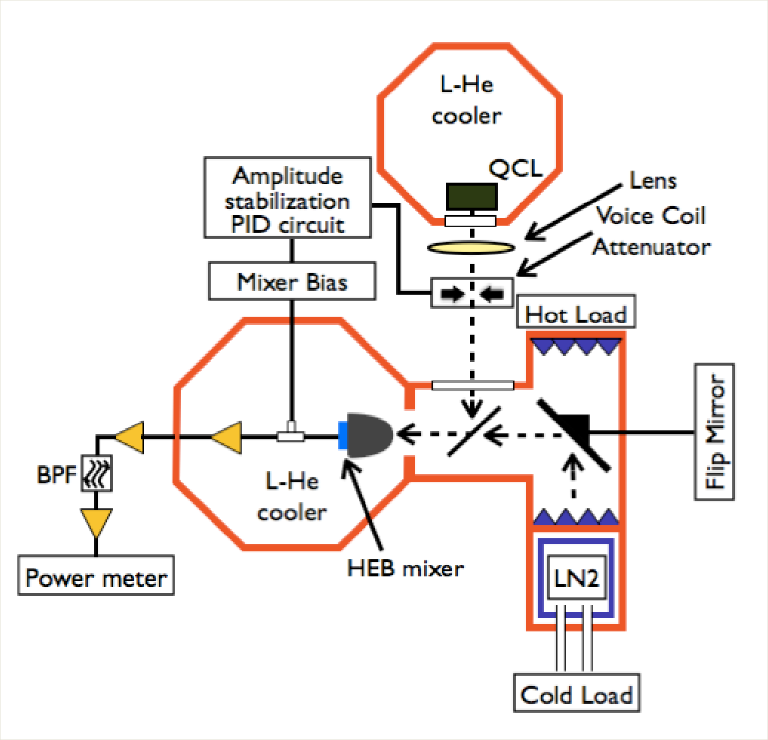


1.8977976 THz
1.8978300 THz
a.u.
1.0
0.8
0.6
0.4
0.2
0.0
200
300
IF #1 (MHz)
IF #3 (MHz)
IF #2 (MHz)
IF #4 (MHz)

4.7 THZ RECEIVER

For the 63 μm fine structure line in atomic oxygen.

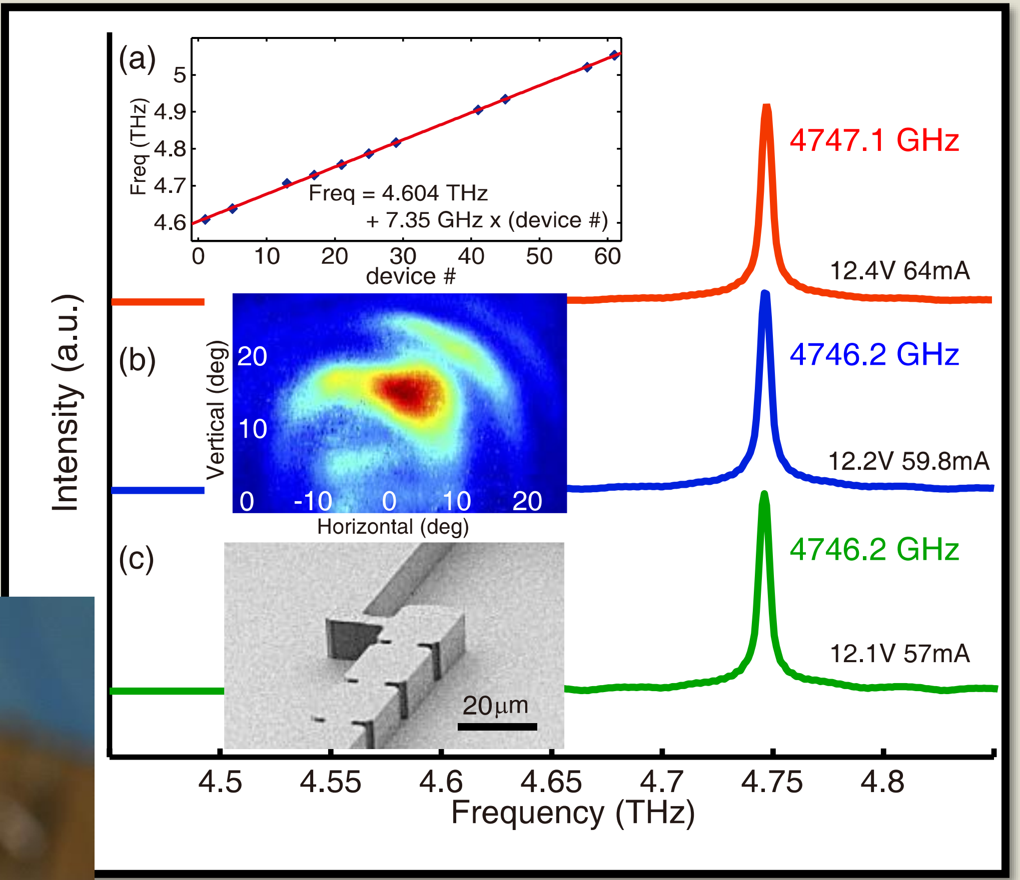
4.7 THz Heterodyne Receiver Laboratory Setup

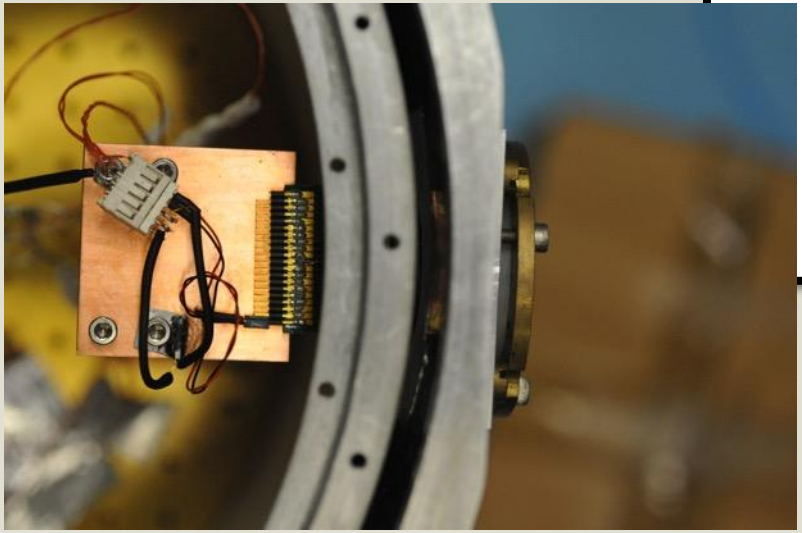


Results from Kloosterman et al. 2013

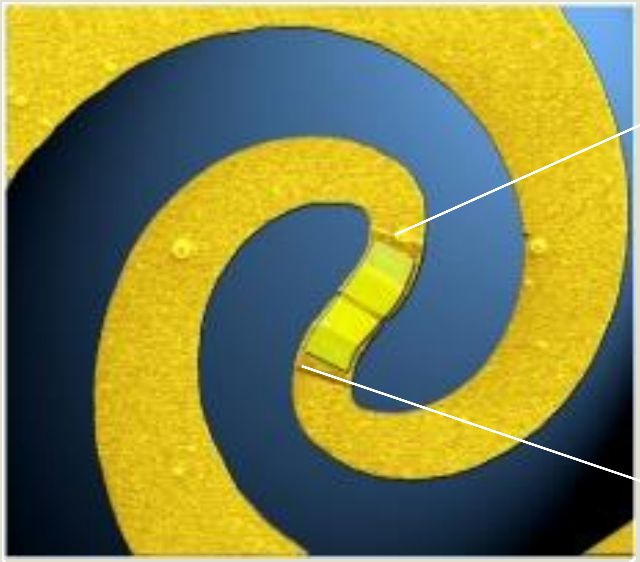
4.7 THz QCL

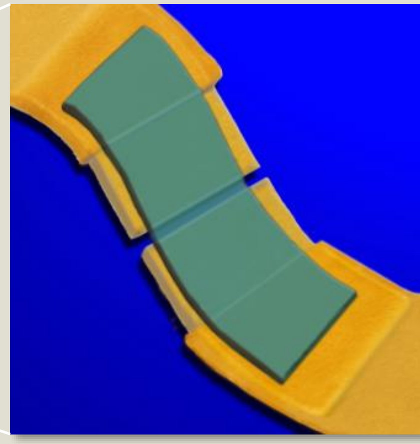
- Tuning range: 1.5 GHz
- Tuning coefficient: 2.4 GHz/V
- THz output: 0.25 mW
- Low power requirement: 0.8 W @ 15 K
- Operation up to 77 K

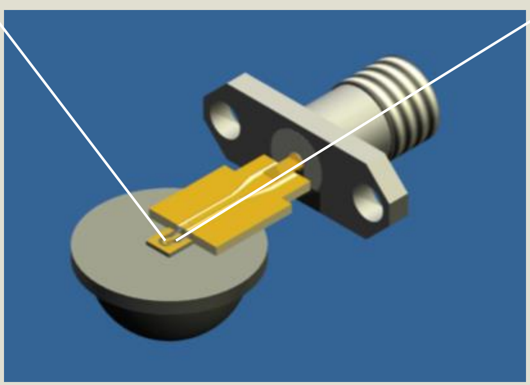


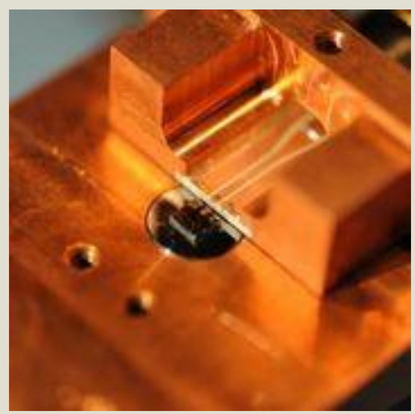


Mixer: Hot Electron Bolometer

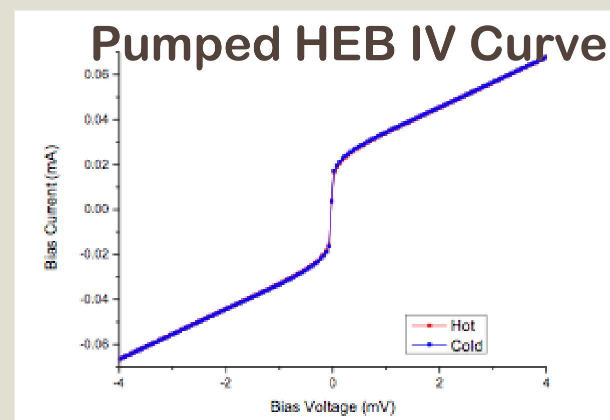




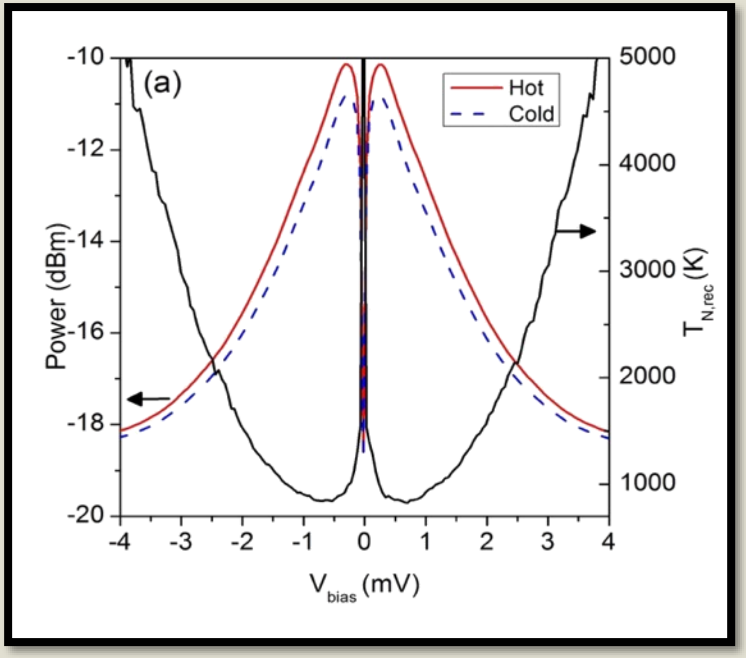


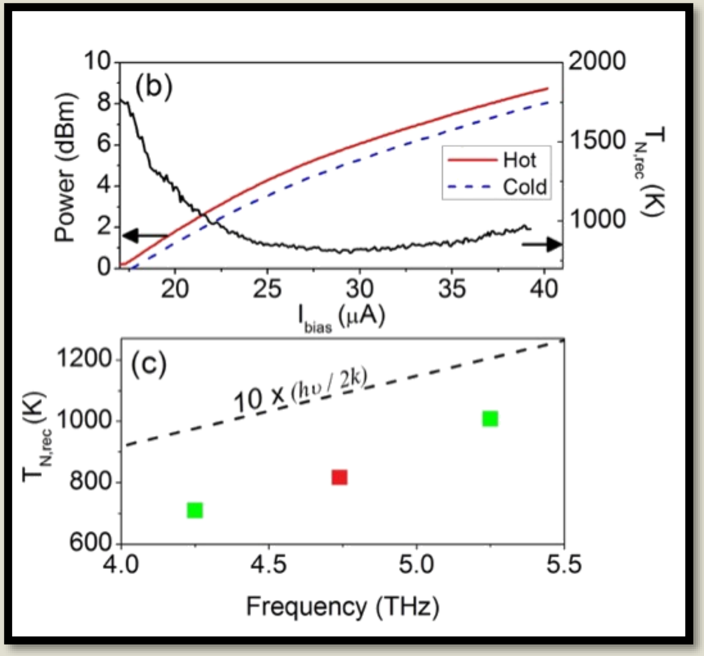


- NbN 2 x 0.2 μm^2 superconducting bridge
- Tight spiral antenna
- Coated Si lens for 4.3 THz



Receiver Noise Temperature



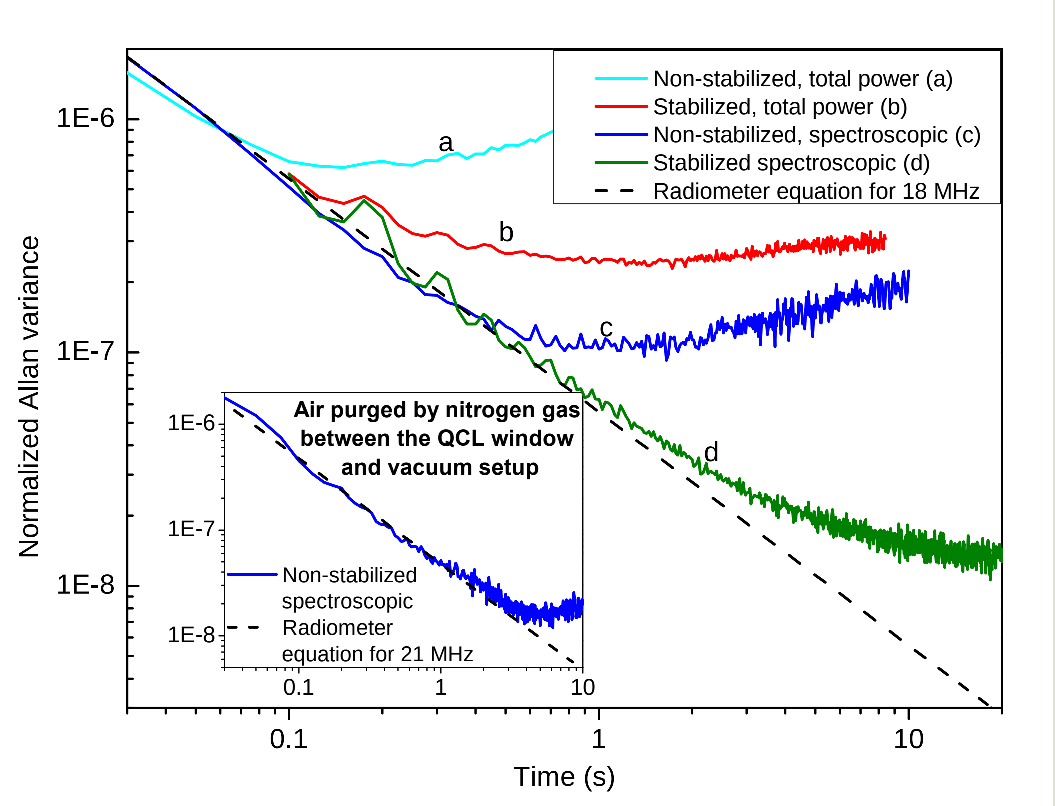


- 3 methods used to measure y-factor at 4.7-THz for an average T^{DSB} = 815 K!!!
- At 4.25 THz, measured 750 K
- At 5.25 THz, measured 950 K

$$T_{N,rec} = \frac{T_{eff,hot} - YT_{eff,cold}}{Y - 1}$$

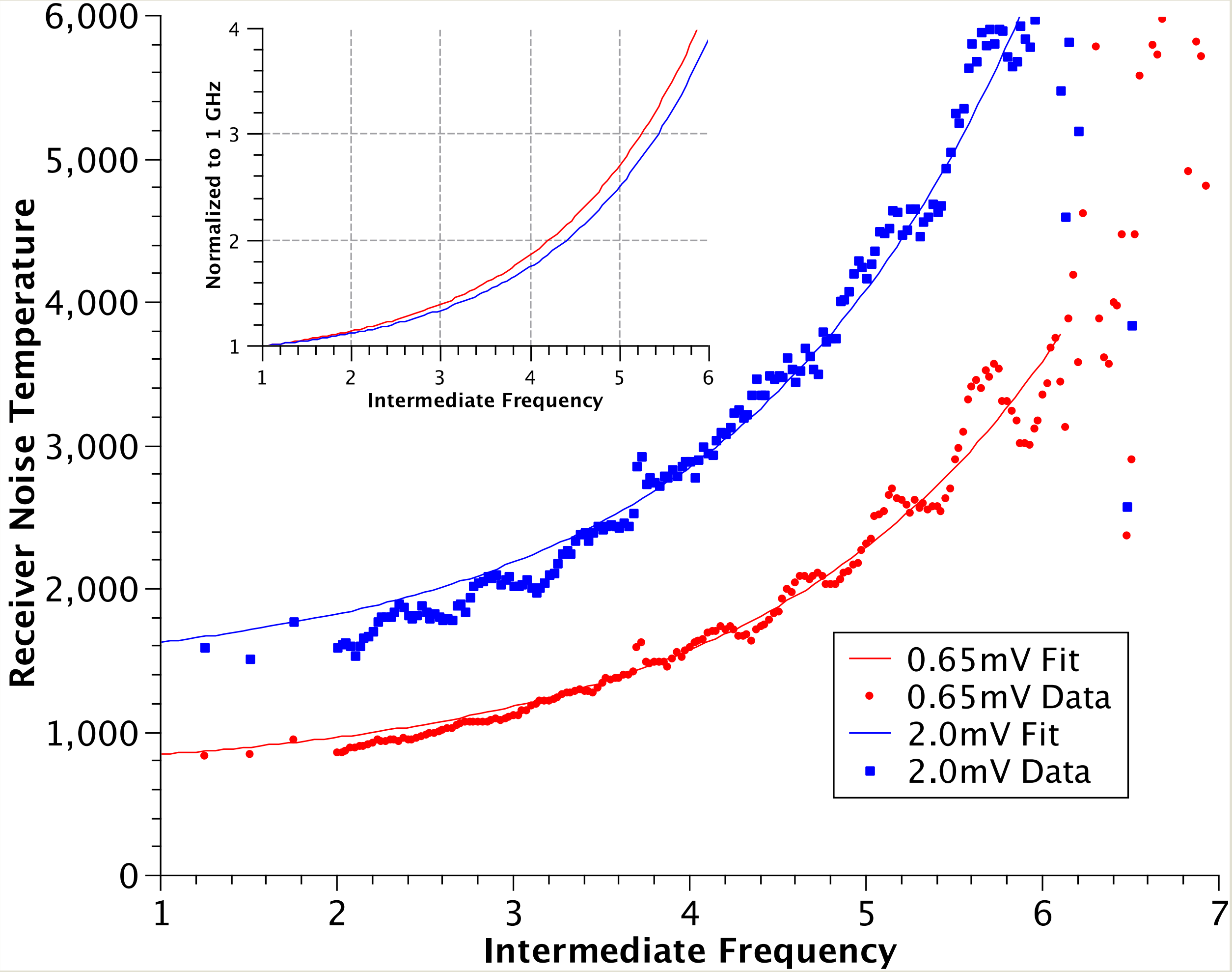
Stability – Allan variance measurements

- Non-stabilized, spectroscopic Allan variance: ~1 second
- Stabilized spectroscopic Allan variance: ~15 seconds
- Nitrogen gas purged (non-stabilized) Allan variance: ~7 seconds
- Suggests that atmospheric turbulence may be a large contributor to instability of the system



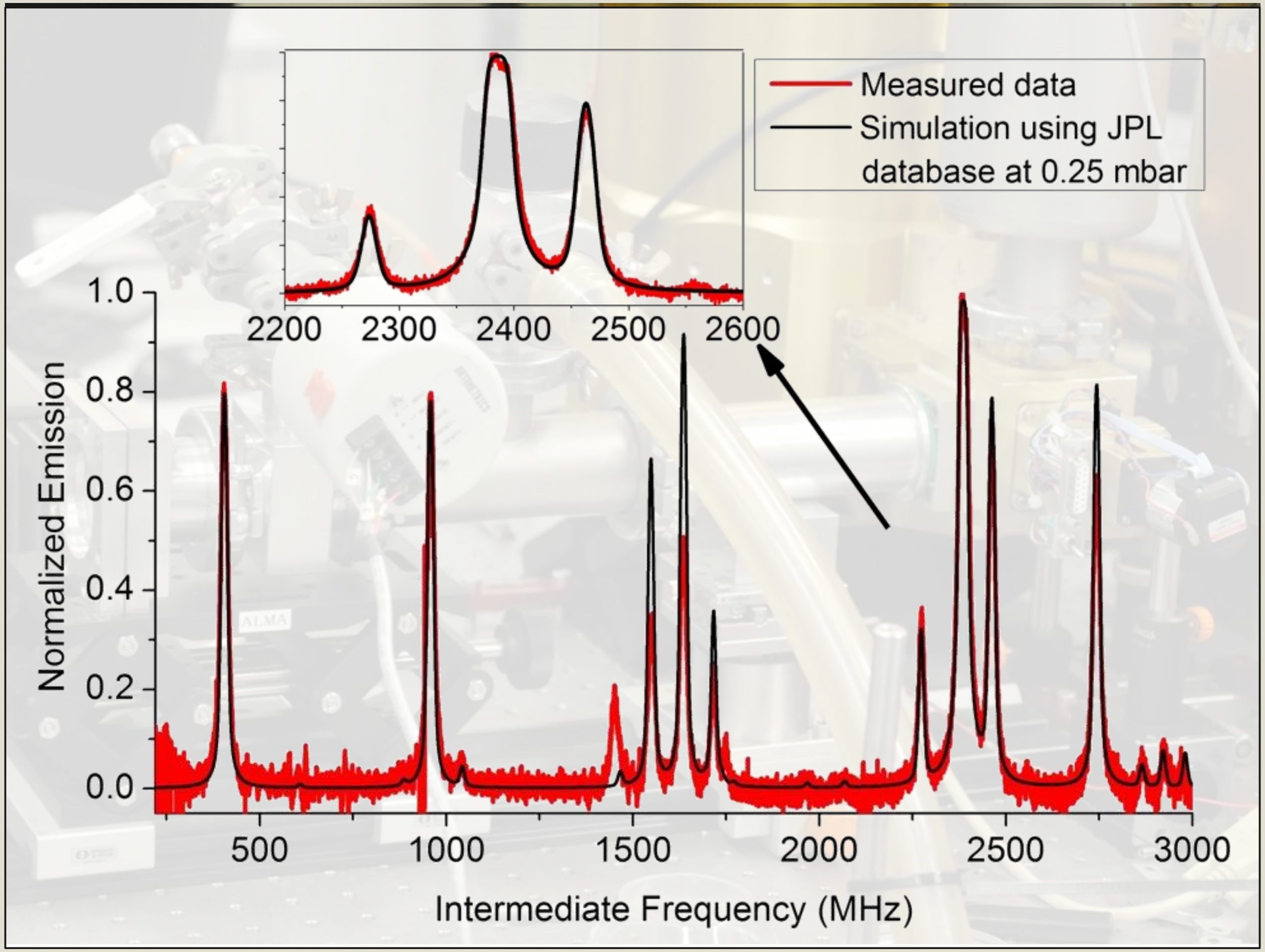
$$\sigma_A^2(\tau) = \frac{1}{2\tau^2(N-2n+1)} \sum_{k-1}^{N-2n+1} [x(t+2\tau) - 2x(t+\tau) + x(t)]^2$$

IF Bandwidth



Methanol Gas Spectroscopy at 4.7 THz

Methanol gas spectroscopy used to verify performance



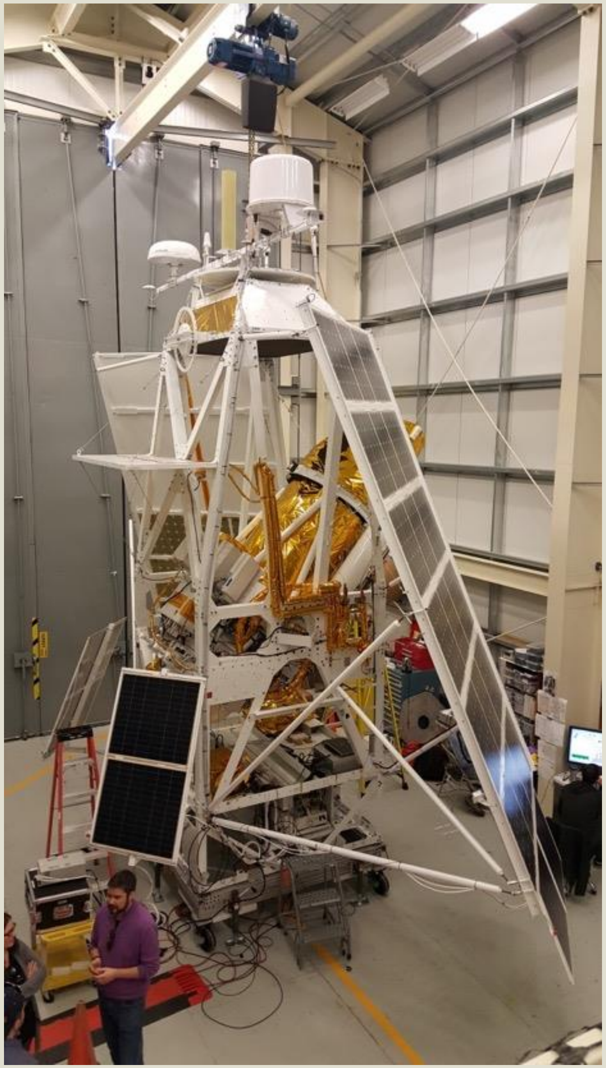
Good agreement with model demonstrates:

- HEB sensitivity
- IF linearity
- Receiver stability
- LO frequency
  - QCL: 4.7404 THz
  - [O I]: 4.7448 THz
  - -> ~4.3 GHz IF

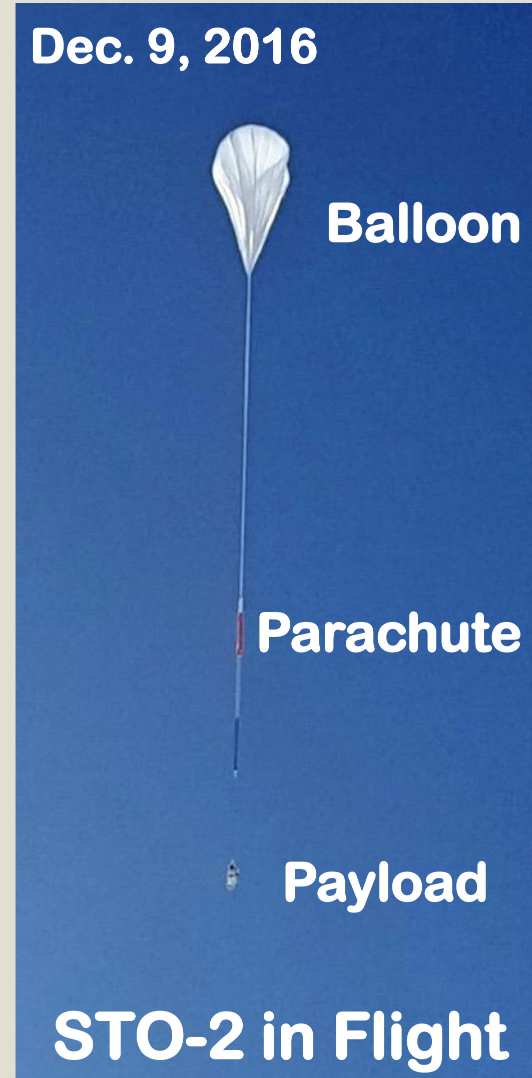
OBSERVING PLATFORM: STO-2

The Stratospheric Terahertz Observatory 2

Stratospheric Terahertz Observatory 2 (STO-2)



Flew 2-pixel receivers at 1.46 and 1.9 THz. Flew 1 pixel at 4.7 THz.

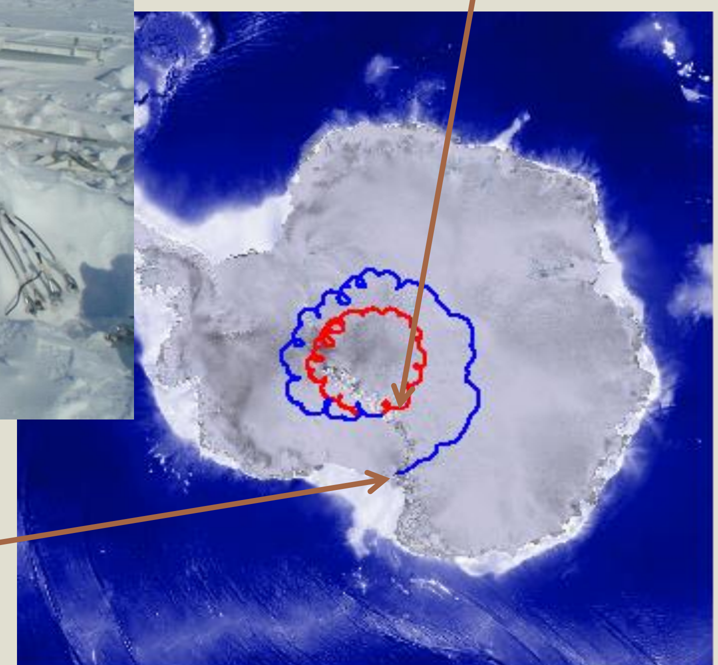


STO-2 **at Launch: Williams Field, Antarctica**

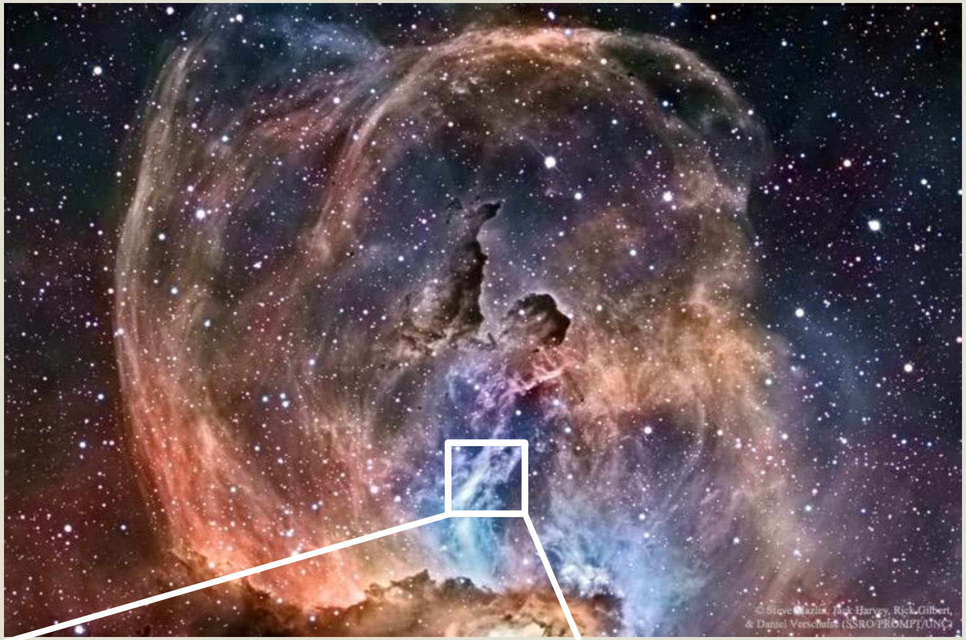
STO-2 Launch 12/9/2017

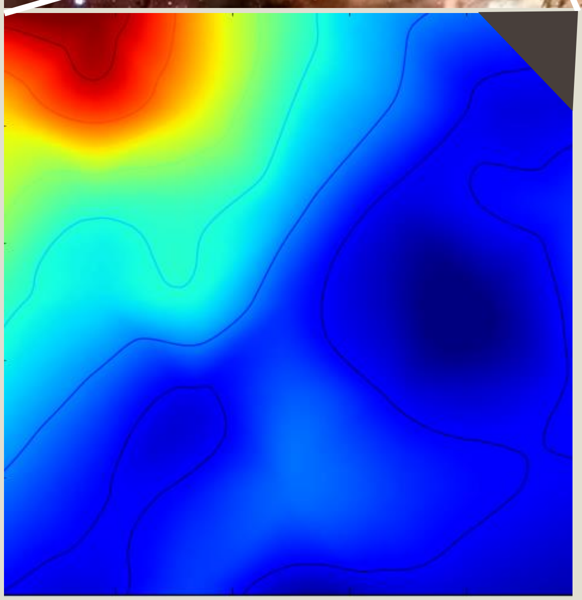
Video courtesy of C. Groppi

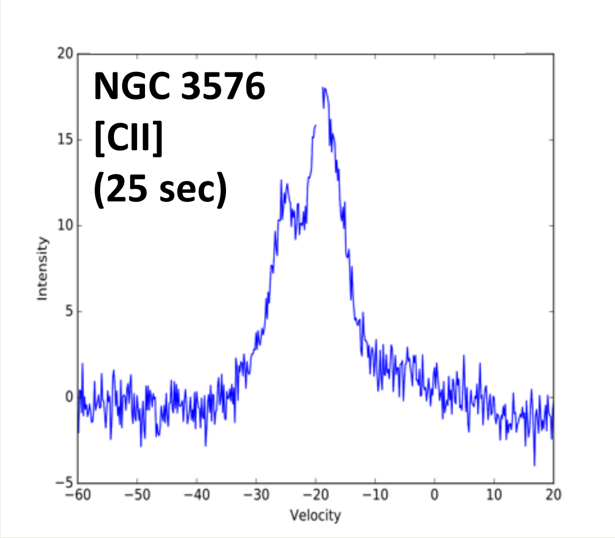
Flight

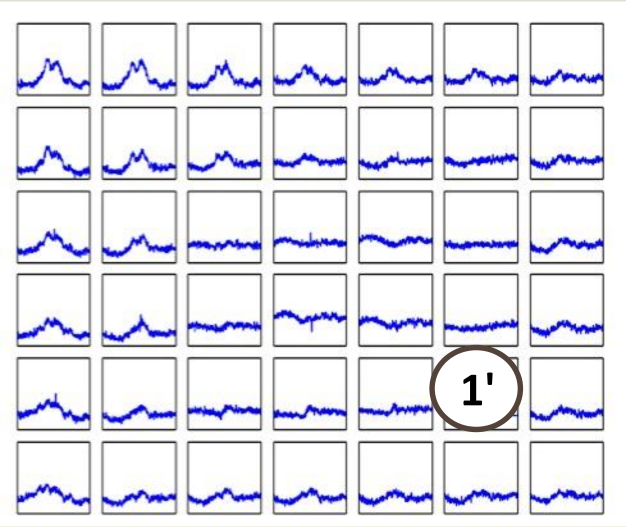


STO-2 First Light: NGC3576









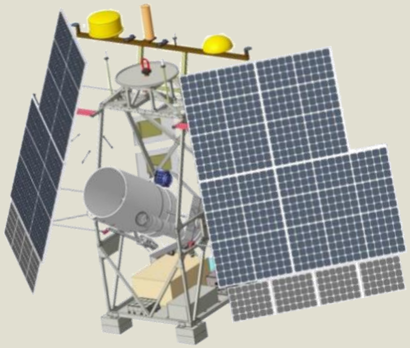
Integrated Intensity

Spectral Mosaic

Observations Summary:
- ~8,000 LOS's in [CII] and [NII]
- Objects: NGC 3576, GL 4176, GL 4182 RCW 38, RCW 92
- Galaxy: G328.0, G310.5

Future Directions

- The Galactic Ultra-Long-Duration Stratospheric Terahertz Observatory (GUSTO) has completed Phase A



- Expand array capabilities to increase mapping speeds

- Develop THz heterodyne instruments for Earth and Planetary Science remote sensing applications

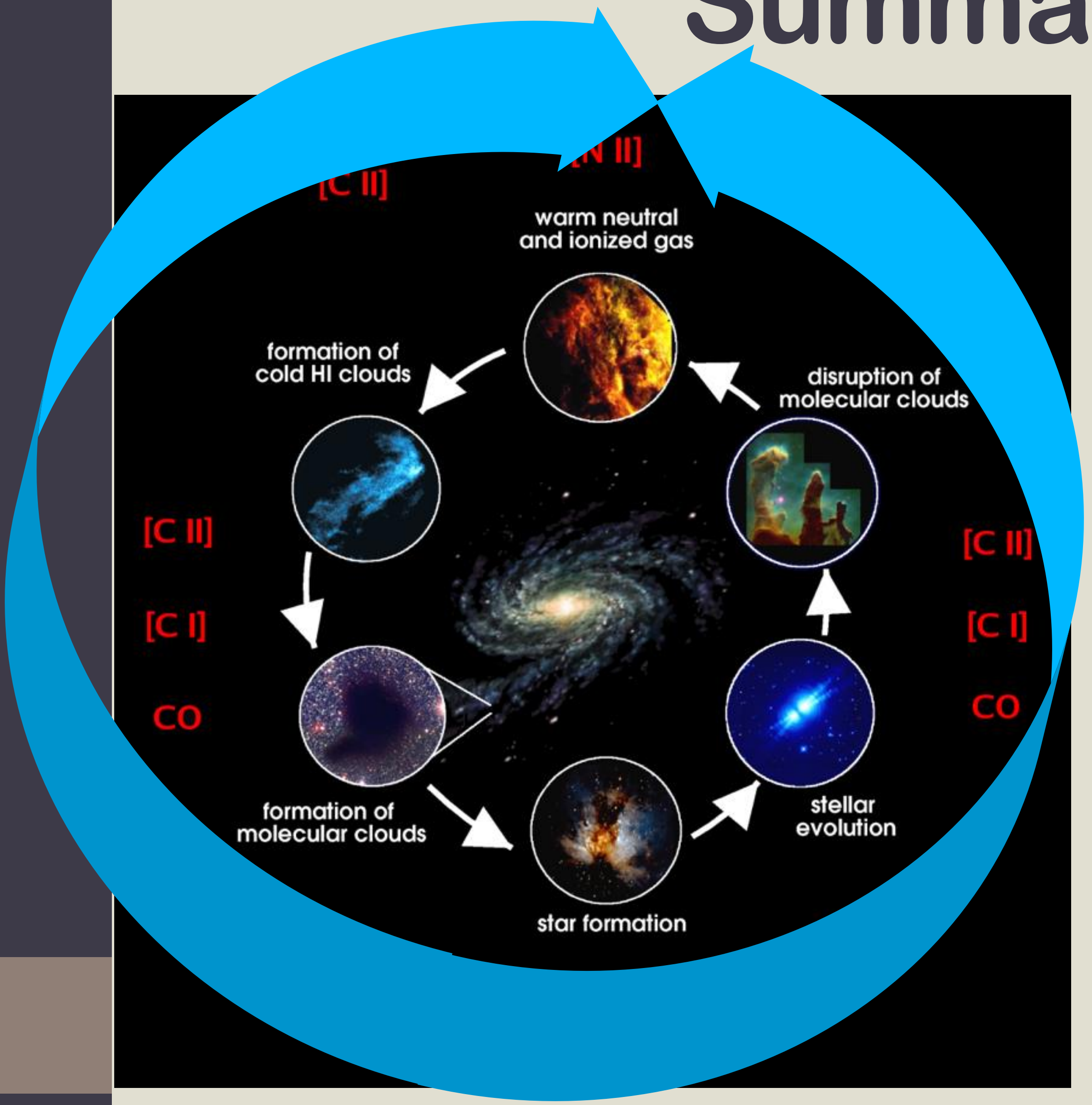
Summary

- We have demonstrated an end-to-end test of a 4x1-pixel heterodyne array receiver at 1.9 THz. The receiver:
  - Has high sensitivity
  - Design is scalable to other frequencies
  - These new designs can be extended into larger arrays by stacking the 4x1 LO and mixer block modules

- 4.7 THz receiver demonstration using QCL as an LO:
  - High sensitivity and good stability
  - Methanol spectroscopy confirms frequency and models at 4.7 THz

- Must get above Earth's atmosphere to observe in the Milky Way
  - Use balloons such as STO-2/GUSTO
  - Airplane – SOFIA
  - Satellite or Flight Mission

Summary

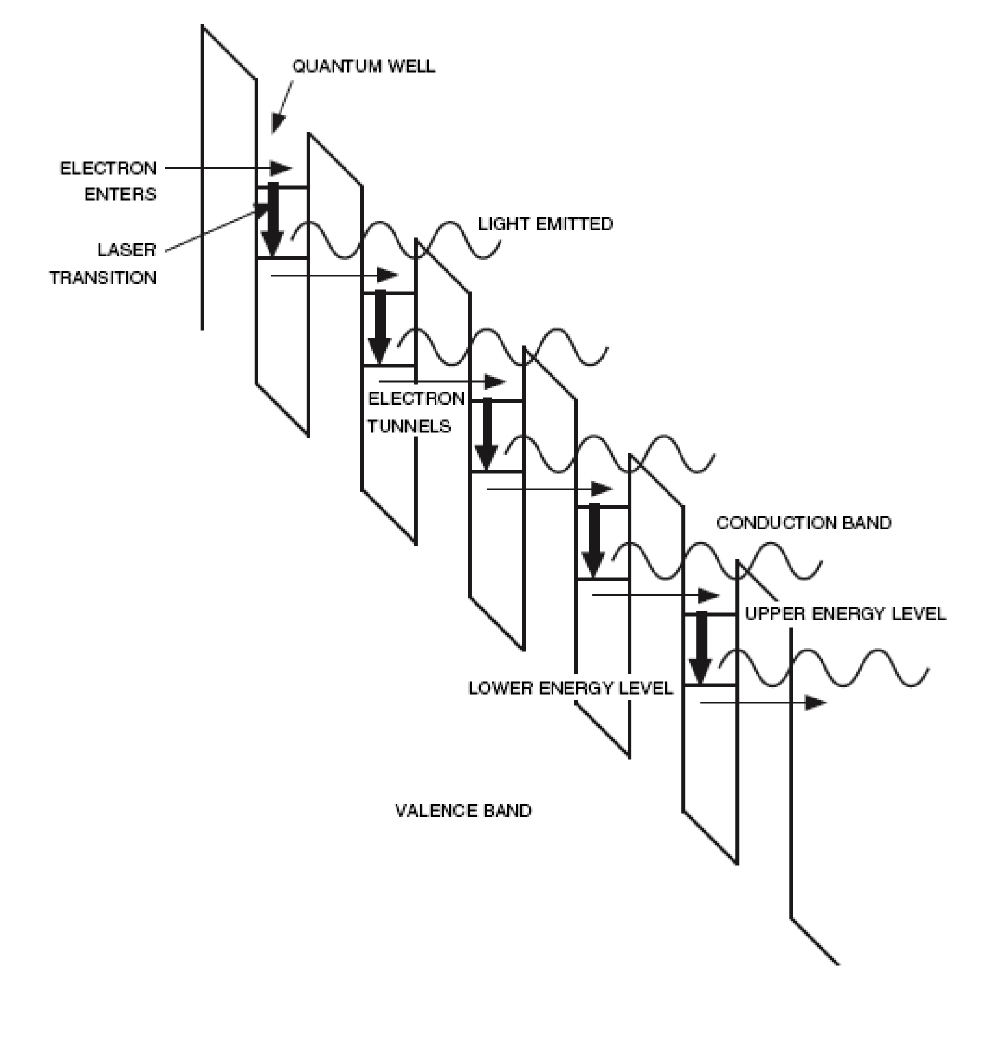


The lifecycle of the Interstellar Medium (ISM); Image Credit: C. Kulesa

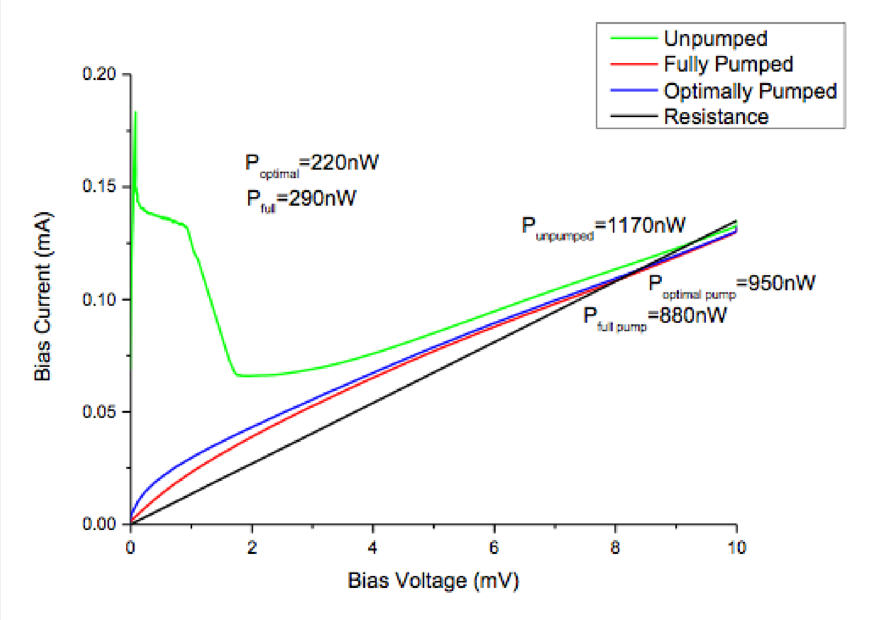
- The study of the lifecycle of the ISM helps to answer questions about our cosmic origins by exploring the dust and gas from which we formed
- Atomic and molecular spectral lines resonate in the THz/sub-millimeter region of the electromagnetic spectrum
- Heterodyne receivers provide sensitivity and high spectral resolution in order to study the kinematics of PDRs/GMCs

Local Oscillator: Quantum Cascade Laser

- A voltage moves free electrons from the valence band to the conduction band
- These electrons tunnel through a quantum well
- A photon is released with the amount of energy lost by the electron
- Repeat



QCL-HEB Coupling Efficiency



QCL Power Loss

- UHMW-PE lens and cryostat windows: **~3 dB**
- Air: **~3.5 dB**
- Mylar beam splitter: **~9 dB**
- IR filter: **~0.8 dB**
- Coated Si lens: **~1 dB**
- Spiral antenna polarization: **3 dB**
- Total: **~21 dB**